PHD

INJURY EPIDEMIOLOGY AND INJURY PREVENTION IN ELITE ENGLISH AND WELSH CRICKET

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INJURY EPIDEMIOLOGY AND INJURY PREVENTION IN ELITE ENGLISH AND WELSH CRICKET

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ABSTRACT

The programme of research presented in this thesis aimed to understand the injury profile of men's domestic and women's international pathway cricket in England and Wales to inform injury prevention strategies that can reduce injury burden in the game.

The first study of this thesis (Chapter 3) establishes the extent of the injury situation in elite senior men's domestic cricket in England and Wales, with bowling the most high risk activity, the thigh the most common body area injured and lumbar spine injuries the most prevalent. Similar injury profiles were found across the three domestic competition formats. Chapter 4 identified a moderate reduction in injury burden to be associated with potentially worthwhile effects on performance for a men's senior domestic cricket team in County Championship Division 1, but not Division 2. This association may be valuable when communicating the importance of injury prevention to First-Class County Cricket (FCCC) club stakeholders. Chapter 5 explored the current injury risk perceptions and injury prevention practices of practitioners working within this environment and found the top perceived risk factors to be previous injury, physical fitness, accumulated fatigue, reduced recovery time, and training load. Communicating the purpose and value of player monitoring was found to be important for buy-in and adherence, which can be facilitated through effective working relationships with key stakeholders. The findings also identified that more needs to be done to support practitioners in cricket with appropriate player monitoring methods and analysis. Chapters 6 and 7 focused on understanding the current injury situation (Chapter 6) and risk factors (Chapter 7) in women's international pathway cricket that should provide practical insights for practitioners working in this rapidly developing area of the sport.

Overall, the findings from this work confirms the importance of injury prevention efforts and communicates their value for all stakeholders in elite men's domestic and women's international development pathway cricket. The knowledge gained from these investigations should also highlight the need for continued consistent data collection, support for practitioners to aid their understanding, effective application of player monitoring practices, and appropriate analysis strategies for the dynamic and complex nature of sport injury data.

PUBLICATIONS

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I spoke to my mother recently who enquired as to whether I had finished my PhD yet. I informed her my submission was imminent to which she remarked that working towards this moment for the last three years must have been arduous and at times traumatic. It made me pause to reflect and the truth is it has never been any of these things, not once. I have loved every minute of completing this work and I have a number of people to thank for this:

Firstly, I would like to thank my tremendous supervisor’s Dr Sean Williams, Dr Carly McKay and Professor Keith Stokes for their unwavering advice, guidance and support throughout this process. I could not have asked for a better supervisory team, and they make such a fantastic team. I have benefitted not just from their individual strengths but also as a collective; the excellence they exude and inspire. From start to finish, it has been an absolute pleasure to work with and learn so much from them.

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ABBREVIATIONS

ACL	Anterior Cruciate Ligament
ACWR	Acute:Chronic Workload Ratio
AFL	Australian Football League
AIC	Akaike Information Criteria
AUC	Area Under the Curve
BCA	Ballarat Cricket Association
CI	Confidence Interval
ECB	England and Wales Cricket Board
EWMA	Exponentially-Weighted Moving Average
FCCC	First-Class County Cricket
GLMM	Generalised Linear Mixed Model
GPS	Global Positioning System
GTI	Gastrointestinal Tract Infection
ICC	International Cricket Council
ICD-10-AM	International Classification of Diseases 10-Australian Modification
MBI	Magnitude Based Inference
MCC	Marylebone Cricket Club
NHST	Null Hypothesis Significance Testing
OSICS	Orchard Sports Injury Classification System
PCA	Professional Cricketers Association
REACH	Research Ethics Approval Committee for Health
ROC	Receiver Operator Characteristic
ROM	Range of Motion
sRPE	Session Rating of Perceived Exertion
SD	Standard Deviation
SIC	Subsequent Injury Categorisation
SPC	Statistical Process Control
T20	Twenty20
TIP	Team-sport Injury Prevention
TRIPP	Translating Research into Injury Prevention Practice
TRIPOD	Transparent Reporting of a multivariable prediction model for Individual Prognosis or Diagnosis
URTI	Upper Respiratory Tract Infection

CHAPTER ONE

Introduction

1.1 Research overview

The game of cricket in England can be traced back to the 16th Century where early collections of match results and scores have been recorded (Underdown, 2006). The game gradually became more professional during the late 1700s, which coincided in part with the formation of the first cricket club in Hambledon in the 1760s and the Marylebone Cricket Club (MCC) in 1787 (Underdown, 2006). Up until the International Cricket Council (ICC) emerged in 1967 as the world controlling body for the sport, the MCC was seen as the main authority (BBC, 2004). In 1997, the England and Wales Cricket Board (ECB) was formed as the single national governing body for all cricket in England and Wales to create one unified body responsible for the management and development of every form of cricket for men and women (ECB, 2018).

Sport England's annual participation rates (tracking National Governing Body funded sport rates between November each year from 2015 to 2019) showed an average 318,375 adults (aged 16+) participated in cricket at least twice a month (Sport England, 2020). Recent developments in game format, with the introduction and increased prominence of the T20 format over the last 10 years (Orchard et al. 2017), the rise and development of the women's game (Munro & Christie, 2018) and success in international competition with England winning the ICC Women's World Cup in 2017 and Men's World Cup in 2019, has opened the sport up to a wider audience.

Over time the game of cricket has developed into three main formats competed domestically within England and Wales today: The County Championship; One-Day Limited Overs; and T20. The County Championship is a first-class domestic cricket competition established in 1890 (ECB, 2018a), currently competed for by eighteen First Class Counties. A first-class match is played over four days between two sides of eleven players, with each team playing two innings each (where one team bats to score runs, and one team bowls to dismiss the batsmen). An inning can end in several ways: When all but one of the batsmen are out (dismissed); The team batting last scores the required number of runs to win; The game runs out of time and so finishes a draw; The set number of overs have been bowled (in limited overs cricket); The team's captain declares the innings closed.

Play continues each day until the completion of a minimum number of overs (an over consisting of six consecutive balls bowled by a single bowler) or until the scheduled cessation time, whichever is later. The minimum number of overs for a First-Class County Championship match is 96 overs on each of the first three days and 80 overs on the last day. Eight teams currently make up Division 1, playing each other on a home and away basis with ten teams in Division 2, each playing five teams home and away and four teams home or away (ECB, 2018b).

The One-Day Limited Over competition is currently competed for by the eighteen First Class Counties, initially split into a North and South Group before proceeding to knock-out stages. Each team bats for 50 overs unless they are all out earlier (ECB, 2018c).

T20 cricket is competed in a similar way to the One-Day Limited Over competition with the eighteen Counties first playing in a league format with two groups (North and South) of nine teams, before proceeding to a knock-out format. Each team bats for 20 overs unless all are out earlier (ECB, 2018d).

It has been proposed player availability (through not being injured) may be as important a factor in team success as player skill (Orchard, 2009), with such unavailability shown to have a negative effect on team and individual athletic success (Drew et al. 2016). Injury epidemiology research has enhanced understanding of injury distribution and causation and led to development of successful strategies to reduce the incidence and severity of injuries (MacKenzie, 2000). Such understanding is extremely worthwhile as injuries are an unfortunate side effect of sports participation (Van Mechelen et al., 1992) that should be prevented wherever possible.

Sport injury models provide a framework to the injury prevention process and increase understanding of the factors that can lead to sport injuries. The most recent injury prevention model is the Team-sport Injury Prevention (TIP) cycle (O'Brien et al., 2019). The model includes three stages; 1) (Re) evaluate, 2) Identify and 3) Intervene. The first phase aims to capture and understand the current injury and injury prevention situation. Once this has been established, injury risk factors and mechanisms are identified in the second phase, which can then inform preventative strategies introduced in the third and final phase. The TIP cycle was intended to provide practitioners with a cyclical process for the dynamic nature of injury prevention in the real-world context of professional team sport. It requires continual progression through the three phases so a team's injury prevention strategy can dynamically evolve, responding to constant changes in the team's environment. To date, no studies in the context of England and Wales cricket have been guided by such a model to inform injury prevention strategies with the aim to reduce injury burden and such work needs to be undertaken.

To enable the study of injuries, injury surveillance programmes have been established across many sports. The aim of such programmes is to promote definitions and guidelines for consistent data collection methods, producing better quality data that can then enhance understanding of the causes and patterns of injuries specific to a given sport. This is in line with phases one and two of the TIP cycle, which then informs the development and evaluation of injury prevention strategies (Ekegren et al., 2016) that are implemented in the third and final phase before being re-evaluated again in the first phase.

In 2005, an international consensus statement was published that set recommended methods and definitions for injury surveillance in cricket (Orchard et al. 2005). It was the first sport to set out such guidelines and while injury surveillance research was being conducted in the sport prior to the consensus, varying methods were deployed, making it impossible to directly compare internationally published studies. The consensus statement was put together with representatives from each test-playing nation where injury surveillance was being undertaken or proposed, which included Australia, England and Wales, South Africa, New Zealand, West Indies and India. The guidelines were effectively deployed by a number of studies across the sport in West Indies (Mansingh et al. 2005), New Zealand (Frost & Chalmers, 2014) and Australia (Orchard et al., 2006; Orchard et al., 2016a) enabling the desired comparison and ability to validate trends and identify differences between countries (Orchard et al., 2005).

Appropriate definitions, units of incidence and prevalence were agreed and put forward in the consensus statement. A significant cricket injury was defined as:

"Any injury or other medical condition that either: 1) prevents a player from being fully available for selection in a match or 2) during a major match, causes a player to be unable to bat, bowl or keep wicket when required by either the rules or the team's captain."

(Orchard et al. 2005, pp. 1)

These guidelines were adopted by studies in New Zealand (Frost & Chalmers, 2012), West Indies (Mansingh et al. 2005) and Australia (Orchard et al. 2006) and consistent findings started to emerge. For instance, pace (also known as fast) bowlers were found to have the highest risk of injury, with hamstring and back the areas with the highest incidence and prevalence. However, the 2005 injury consensus statement did not include recommendations relating to T20 cricket. Due to its shorter duration, the match injury incidence units (per 10,000 player hours) proposed in the original consensus over-estimated the incidence for this competition format.

A more standardised unit that reported match injury incidence in days (per 1,000 player days) as opposed to hours was proposed (Orchard et al., 2010) and included in the updated international consensus statement for injury surveillance in cricket (Orchard et al., 2016b). The consensus statement was revised not just due to the rise of T20 cricket, but to also include non-time-loss injuries (Mitchell and Hayen, 2005; Hodgson et al., 2007), which were excluded from the original consensus. In the updated consensus statement, Orchard et al. (2016b) also suggested an annual unit of injuries per 100 players per year, which allowed for match, training, gradual and insidious onset injuries to be combined into one measurement. It was hoped the updated guidelines provided consistent definitions that offered greater flexibility to researchers to choose methods that suited their study type, which would enable comparison not just within cricket but also between different sports.

For injury surveillance to yield meaningful insight, there needs to be enough longitudinal injury surveillance data from a country to enable the identification of trends over time, whilst reducing any potential confounding variables that may arise when comparing general trends between countries and the different conditions associated with each unique environment. This has been possible in Australia, where injury surveillance has been ongoing and reported from 1995 to 2016 (Orchard et al., 2006; Orchard et al., 2016a).

The ECB Injury Surveillance Programme was established in 2010 for the men's domestic game and 2015 in the women's international pathway to conduct injury surveillance with consistent methodology across all First-Class County and international teams. This longitudinal data provides an excellent platform for establishing the current injury situation and investigating risk factors in these populations. This data has never collectively been formally analysed, but will be as part of this PhD, commissioned and funded by the ECB and University of Bath. The overarching aim of this work was to understand the injury profile of men's and women's cricket in England and Wales, to inform future prevention strategies that could lead to a reduction in injury burden within the sport.

Accordingly, the following research questions will be addressed:

i. What is the injury profile of men's domestic county cricket and how does this differ between game formats?
ii. Is there an association between injuries and team success in domestic country cricket?
iii. What are the current perceived injury risk factors and player monitoring practices of practitioner's in men's domestic country cricket?
iv. What is the injury and illness epidemiology of the women's international pathway cricket and what influences player availability?
v. What are the injury risk factors in women's international development pathway cricket?

1.2 Thesis overview

Data analytics can be categorised in three ways; as descriptive, predictive (using factors to predict, mapping inputs to outputs), or predictive using counterfactual, causal inference framework (Hernán et al., 2019). An overview of each chapter is provided below along with the type of data analytics used to address the research questions.

1.2.1 Chapter 2: Literature review

A review of literature related to the aforementioned research questions is provided in Chapter 2. This includes literature on theories of injury causation and injury prevention, and methodological issues related to the recording, reporting and analysis of sport injury data. Intrinsic and extrinsic risk factors for injury are also discussed.

1.2.2 Chapter 3: Descriptive injury epidemiology of elite men's domestic senior cricket

This chapter was the largest formal analysis of men's domestic cricket injuries in England and Wales to date to address the first research question. In line with Hernán et al's (2019) data analytics categorisations, this chapter used descriptive analytical techniques, with injury incidence and prevalence rates used to summarise the nature of injuries in this population, and overall effects of match format, activity at time of injury, and body region injured were determined. Statistical Process Control charts visualised the injury trends over the nine seasons the data was collected for.

1.2.3 Chapter 4: Association between injuries and team success in elite men's domestic county cricket

An investigation of the association between injuries and team success in elite men's domestic county cricket is presented in Chapter 4. To answer the second research question, predictive models were used, with factors as inputs mapped to outputs (Hernán et al., 2019). Linear mixed modelling techniques were used to assess the relationship between within-team changes in injury measures (inputs) on County Championship points (output), which was the marker of team success. Between-team effects were analysed with correlation co-efficient to determine how injury measures of teams that were on average more successful over the study period compared to those less successful (lower average points tally). Magnitude-based inferences were used as a complimentary analysis to evaluate and interpret the effects in terms of practical relevance.

1.2.4 Chapter 5: Current practitioner perceptions of injury risk factors and player monitoring practices in elite men's domestic cricket

Chapter 5 utilised descriptive analytical techniques (Hernán et al., 2019) with a mixed-methods approach to capture and better understand the current practitioner perceptions of injury risk factors and player monitoring practices in elite men's domestic senior cricket, to answer the third research question. A quantitative survey was sent to science and medicine practitioners at all 18 First-Class County Cricket (FCCC) clubs to identify and quantify injury risk factor perceptions, with follow up qualitative interviews (with a subset of these practitioners) to explore in more depth, current player monitoring practices.

1.2.5 Chapter 6: Injury and player availability in women's international pathway cricket

This chapter can also be categorised as descriptive (Hernán et al., 2019), outlining for the first time, the injury and illness epidemiology within women's international pathway cricket, thus addressing the fourth research question. Injury incidence and prevalence rates were summarised to describe the nature of injuries in this population, and overall effects of injury type, activity at time of injury and body region injured were determined.

1.2.6 Chapter 7: Injury risk factors in women's international pathway cricket

The study presented in Chapter 7 explored how algorithmic models may be able to identify what risk factors are most important for predicting injury in this setting. Two supervised learning techniques (a decision tree and random forest) and generalised linear mixed effect models were used to identify important injury risk factors and assess their association with injury, using predictive techniques again to map inputs to outputs (Hernán et al., 2019), answering the fifth and final research question.

1.2.7 Chapter 8: Discussion

A discussion of the key findings and conclusions of the thesis are presented in Chapter 8, considering the research questions outlined in Section 1.1. The various methodological approaches adopted through the thesis and the contribution made to existing knowledge are discussed. Suggestions are also provided on the practical implications of the findings and directions for future research.

CHAPTER TWO

Review of Literature

2.1. Overview

This chapter will provide an overview of the literature relating to sport injury epidemiology in cricket, which will include theories of injury causation, considerations with reporting sport injury data, and risk factors specific to injury in cricket. The aim is to provide context and justify the purpose of the current research.

2.2 Injury epidemiology

Epidemiology has been defined as the study of the distribution and determinants of health-related states or events in specified populations (Last, 1995). As such, injury epidemiology is the study of the distribution and determinants of injury and safety related states-events in specified populations (Sadeghi-Bazargani, 2012), or in the case of this PhD, sport-specific groups.

There are two types of epidemiologic research: descriptive, which is the quantification of injury occurrence and describes who is affected, where and when injuries occur and the outcome; and analytic epidemiology, which aims to explain why and how injuries occur and identifies preventative strategies (Caine et al., 2008). Injury epidemiology research has enhanced understanding of injury distribution, causation and risk factors that led to development of successful strategies to reduce the incidence and severity of injuries (MacKenzie, 2000). Such understanding is extremely worthwhile as injuries are an unfortunate side effect of sports participation (Van Mechelen et al., 1992) that should be prevented wherever possible.

2.2. Theories of injury causation

An injury is a mechanical disruption of tissues resulting in pain (Kumar, 2001) when energy to a tissue exceeds the body’s ability to maintain its structural and/or functional integrity (McIntosh, 2005). Four main theories have been developed in non-sporting contexts to further explain this, with the central assumption that occupational musculoskeletal injuries are biomechanical and that any disruption of mechanical order is dependent on the mechanical properties of individual components (Kumar, 2001). Due to the relevant application of these theories to sporting injuries, a brief overview of each will be presented in this section.

2.2.1. Cumulative load theory

Cumulative load theory states biological tissues, like any other physical material, are subject to wear and tear with repeated load application resulting in cumulative fatigue. This in turn reduces their stress-bearing capacity and the threshold stress at which tissues fail (Kumar, 1990). Initial empirical evidence for this theory was provided by a strong association found between cumulative load (biomechanical load resulting from work undertaken and exposure in time over working life) and back pain. Back pain prevalence was 62% in the sample of 161 American health and social workers, with those reporting pain similar to those who did not in age, weight and height (Kumar, 1990). In sport, cumulative load theory helps define overuse injuries that can lead to tissue maladaptation, where the injury has no clear onset, but occurs gradually over time, with a progressive manifestation of clinical symptoms or functional limitations (Soligard et al., 2016).

2.2.2. Overexertion theory

Overexertion theory states that the interaction of force, exposure and range of motion (more than the neutral range) for a given task creates a level of risk for that activity, which if exceeded (based on individual limits set by tissue level tolerance) can result in injury (Kumar, 1994). This theory also highlights the role of recovery (in relation to exposure), with insufficient recovery of a tissue creating a residual effect from each contraction that will gradually build fatigue, with the risk of injury growing with the residual stress (Kumar, 1994). This theory may explain the high incidence and prevalence of lumbar spine injuries (particularly for fast bowlers) in cricket, with the interaction between range of motion that exceeds the neutral range (or natural posture) and exposure particularly pertinent.

2.2.3. Differential fatigue theory

Occupational activities can engage antagonistic pairs of muscles resulting in different loads placed on the muscles, especially when motions are repeated and/or asymmetric as can often be the case. Consequently, the muscles are susceptible to fatigue at varying rates, a concept tested with electromyography studies to measure fatigue in time of different trunk muscles during rotation from a neutral posture in healthy subjects (Kumar and Narayan, 1998). A significant difference was found between individuals in the fatiguing rate of different muscles around the trunk, which could create a force imbalance resulting in quick, substantial loads on already stretched soft tissues. This in turn would cause load beyond the tolerance of the tissue that may lead to an injury (Kumar and Narayan, 1998). In cricket this may relate to injuries from repeatedly-performed techniques such as batting and bowling.

2.2.4. Multivariate interaction theory of musculoskeletal injury precipitation

This theory proposes musculoskeletal injury is the result of an interaction between genetic, morphological, psychosocial and biomechanical factors, each of which contain their own variables that can enhance and affect injury precipitation (fig 2.1). For every individual, each variable has a relative weighting and an injury can be caused from an interaction between these weightings and the degree to which they have been stressed (Kumar, 2001). Given the individual differences of these variables, there is an endless number of possible combinations that may result in injury. In sport, these variables can be related to intrinsic (e.g. individual strength and conditioning, previous injury history) and extrinsic risk factors (e.g. workload) for injury precipitation.

2.2.5. Summary

Injuries are proposed to occur when energy to a tissue exceeds the body's ability to maintain its structural and/or functional integrity (McIntosh, 2005). Four main theories have been outlined, which were developed in non-sporting contexts but have relevance and application to enhancing understanding of sporting injuries. While the theories explain the immediate mechanism of injury precipitation, they can operate simultaneously and interact to modulate injuries to varying degrees in different individuals (Kumar, 2001).

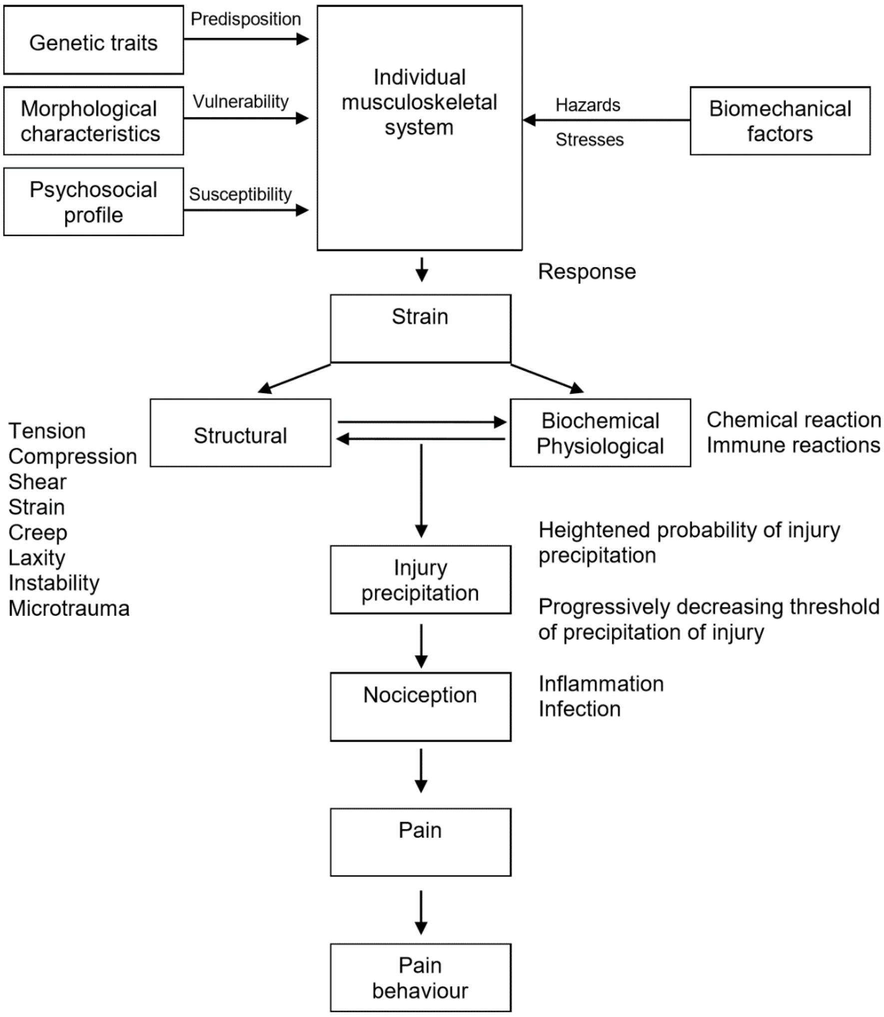

Figure 2.1: Multivariate Interaction Theory of Musculoskeletal Injury Precipitation (Kumar, 2001)

2.3. Sport injury models

Sport injury models provide a framework to the injury prevention process and increase understanding of the factors that can lead to sport injuries. This section will outline the key sport injury models proposed in the literature starting with injury prevention before moving on to injury aetiology.

Injury prevention

2.3.1. Sequence of prevention model

The 'sequence of prevention' model was one of the first sports injury prevention model proposed by Van Mechelen et al. (1992) that was translated from the standard public health prevention model and included a four-step process for sports injury prevention. First, the extent of the problem is established, and then the injury risk factors and mechanisms are identified in the second stage. In the third stage, preventive strategies are introduced, with their effectiveness assessed in the final fourth stage by repeating stage one (fig 2.2).

Although this four-stage model has guided injury research it is suggested to have limited application in practice, with the initial general sports injury research field often struggling to move beyond stage two (Chalmers, 2002; Bahr and Krosshaug, 2005). This is due to sports injury research often only reporting descriptive injury incidence as well as being limited by the research methodology deployed (Finch, 2006). Limitations of existing studies include collecting data through self-report measures that are susceptible to recall bias, as well as differences in injury definitions and statistical methods. The challenge for studies aiming to identify injury mechanisms and risk factors, as outlined in stage 2, is overcoming the practical difficulties of undertaking such analytic studies. Injury incidence for particular sports and for particular injuries (if examining mechanisms for specific injuries) can be low. It has also been proposed that there may be a lack of adequate or appropriate measures to sufficiently capture injury risk factors in such a dynamic and complex environment (Chalmers, 2002). However, the initial four-stage model has been a valuable tool that has guided initial sports injury research, providing a necessary structure for researchers to start building the empirical base for this area.

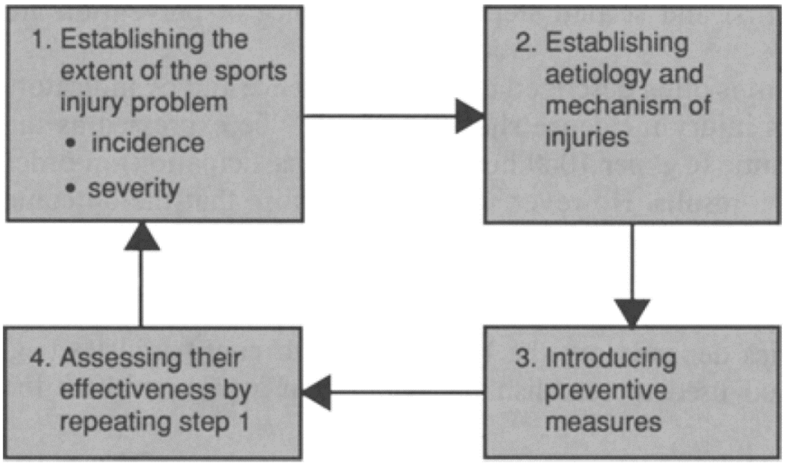

Figure 2.2: The 'sequence of prevention' of sports injuries (van Mechelen et al., 1992)

2.3.2. Translating research into injury prevention practice framework

As useful as the 'sequence of prevention' model (Van Mechelen et al., 1992) has been, it did not consider how such preventative measures (that are introduced in stage three and evaluated in stage four) are practically applied and implemented. This led to the development of the ‘translating research into injury prevention practice framework’ (TRIPP), which added two stages to the four outlined in the original ‘sequence of prevention’ model (Finch, 2006). The fifth stage seeks to understand how any outcomes of efficacy research can be translated into practical application in the real-world context of on-field sports behaviours. This requires knowledge of the current safety behaviours undertaken, and if they are widely adopted. If it is found such proposed outcomes are not being widely adopted, then a better understanding of the potential barriers is required to inform any actions that might be needed to overcome them, to facilitate increased adoption and adherence across key stakeholders. The final stage evaluates how effective a scientifically proven intervention (as shown to be effective in stage four, with understanding on the necessary cues to action within the context of a sport’s culture to enhance implementation in stage 5) is when applied in a real-world setting (fig 2.3). These two additional stages were intended to facilitate the acceptance, adoption and adherence of sports injury prevention interventions by their target users (Finch, 2006).

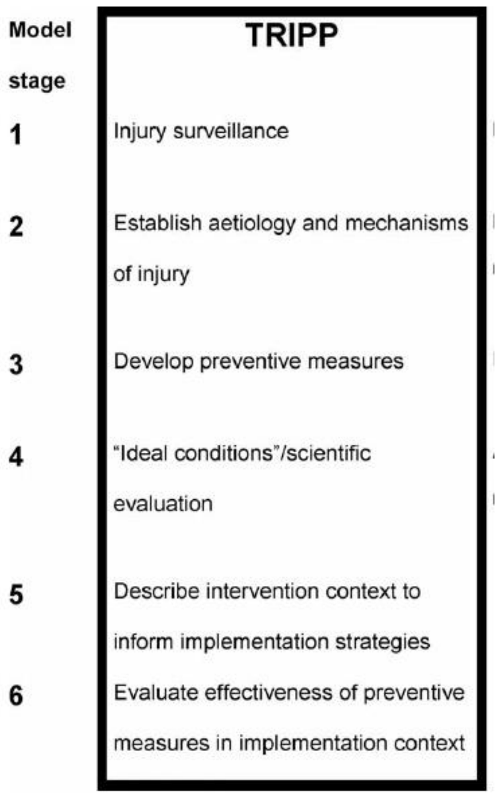

Figure 2.3: Translating research into injury prevention practice (TRIPP) framework (Finch et al., 2006)

2.3.3. Team-sport injury prevention cycle

The applicability and relevance of each of the aforementioned models is context-dependent, with the majority of models focused on injury prevention research and not necessarily how such models can be applied by sports science and medicine practitioners. The Team-sport injury prevention (TIP) cycle was developed with the aim of providing a simple, continual cycle for sports practitioners that incorporated key aspects of the previous models with practical implementation for those working within team sports (O'Brien et al., 2019). The model includes 3 stages (fig 2.4); 1) (Re) evaluate, 2) Identify and 3) Intervene. The first phase aims to capture and understand the current injury and injury prevention situation. Once this has been established, injury risk factors and mechanisms are identified in the second phase, which can then inform preventative strategies introduced in the third and final phase. The TIP cycle was intended to provide practitioners with a cyclical process for the dynamic nature of injury prevention in the real-world context of professional team sport. It requires continual progression through the three phases so a team's injury prevention strategy can dynamically evolve, responding to constant changes in the team's environment.

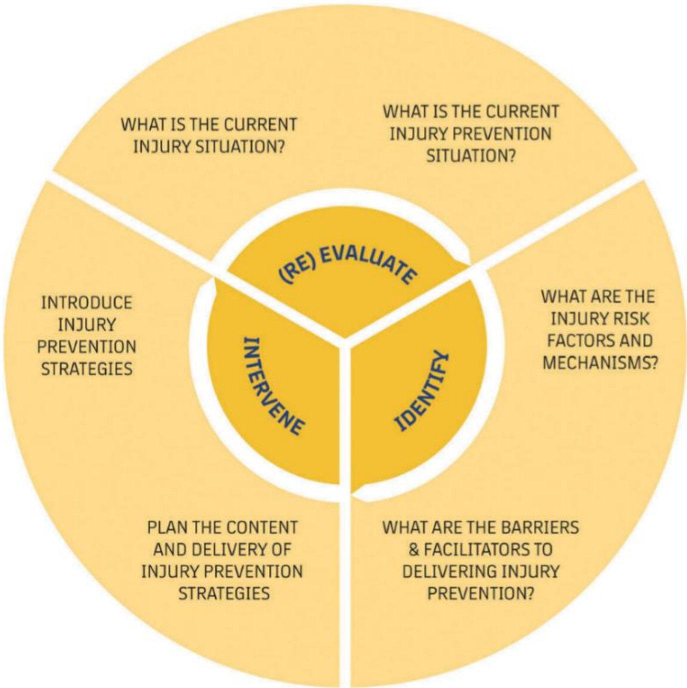

Figure 2.4: Team-sport Injury Prevention Cycle (O'Brien et al., 2019)

Injury aetiology

2.3.4. Multifactorial model of aetiology

Though the TRIPP and TIP models developed the original 'sequence of prevention' to include steps focused on the implementation of an injury prevention measure, neither overcome the noted challenges associated with stage two and the effective identification of injury risk factors and mechanisms. Meeuwisse (1994) attempted to overcome this shortcoming of the original model by providing a more detailed framework specifically for this stage, by incorporating the interaction of internal and external risk factors. Meeuwisse's (1994) multifactorial model of aetiology was based on a modification of work in infectious disease. It described the interaction between an indefinite number of internal predisposing risk factors, which include age, gender, previous injury history and exposure to extrinsic risk factors such as playing time, position, type of playing surface and weather. These risk factors leave an athlete susceptible to injury before an injury-inciting event occurs, whether this is through direct impact or overuse injuries that progressively develop over time (fig 2.5).

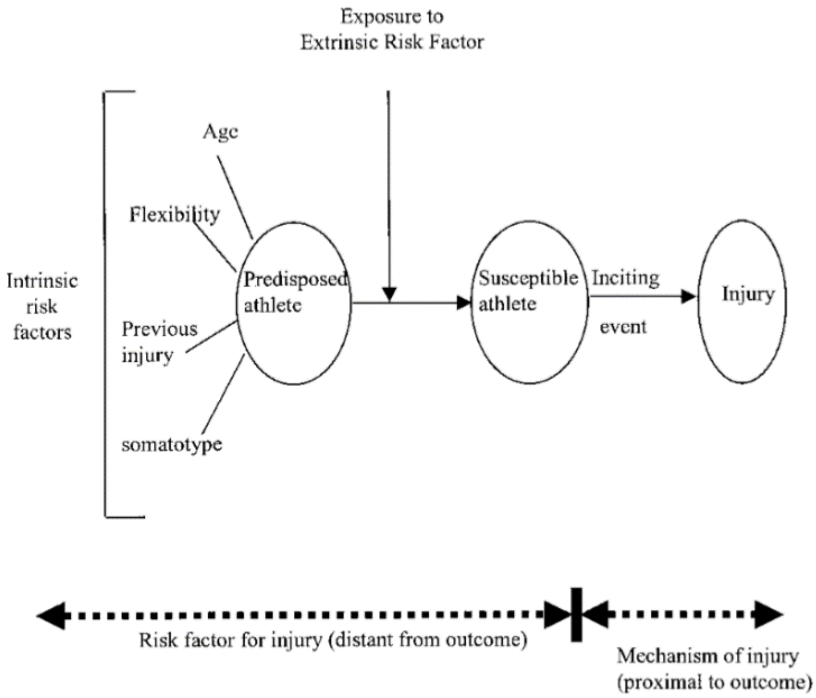

Figure 2.5: Multifactorial model of aetiology (Meeuwisse, 1994)

The characteristics of these injury-inciting events were explored further by Bahr and Krosshaug (2005) to better understand the causes of a particular injury type. The importance of events leading up to an injury inciting event, such as the playing situation and behaviour of the player/opponent, are combined with detailed biomechanical descriptions of the injury to provide a more comprehensive model (fig 2.6).

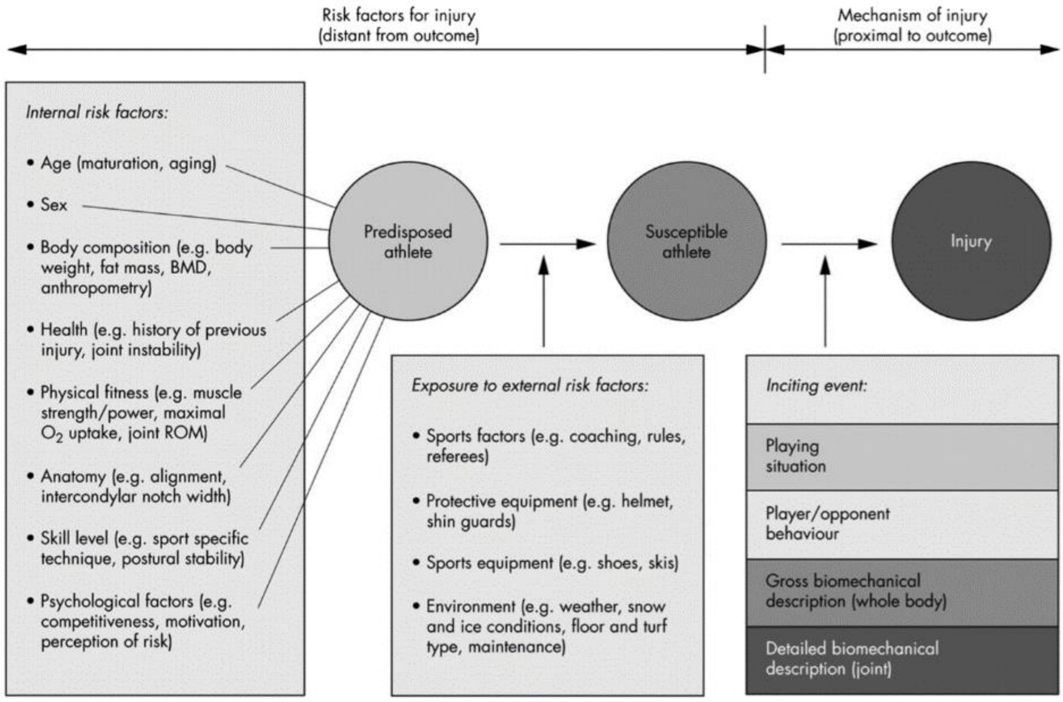

Figure 2.6: Bahr and Krosshaug's (2005) further developed aetiology model from the original multifactorial model of aetiology proposed by Meeuwisse (1994)

2.3.5. Cyclical operational model to investigate contact sport injuries

The cyclical operational model for the investigation of contact sport was developed to overcome the proposed limitation of the multifactorial model of aetiology being too simplistic as a linear model (Gissane et al., 2001). It was suggested the intrinsic risk factors included in Meeuwisse's (1994) original model are not fixed and in fact vary over time. What's more, there is no start and end-point with sports injuries and the linear model does not account for what happens after injury, how the athlete returns to sport and the lasting impact the injury will have on an athlete's susceptibility to injury, which changes with each injury and rehabilitation (Gissane et al., 2001).

Although this cyclical operational model to investigate sport injuries was originally developed for contact sport injuries, the five linked stages contained in the model (and the inclusion of an injury outcome) have relevance to non-contact sport injuries also. The model begins with a healthy/fit athlete with several intrinsic risk factors that with or without additional exposure to extrinsic risk factors in the presence of a potential injury event, can result in injury (Gissane et al., 2001). Then the duration of the injury, treatment and rehabilitation produces an ultimate outcome that can either be a return to sport at the original level (completing the cycle), returning at a lower level or possibly being forced to prematurely retire from the sport (fig 2.7).

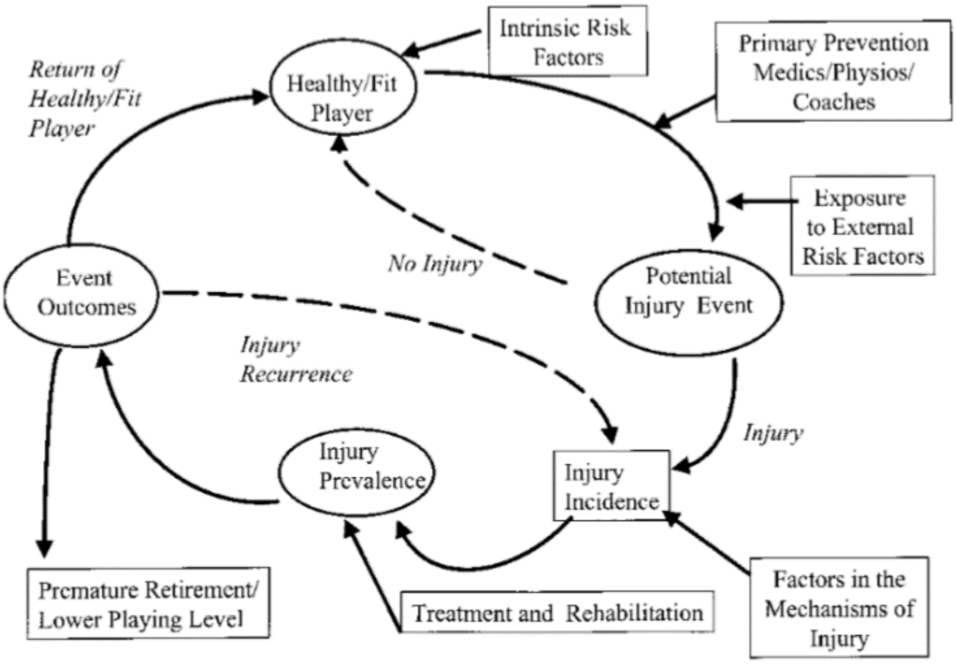

Figure 2.7: Cyclical operational model for the investigation of contact sport injuries (Gissane et al., 2001)

2.3.6. Dynamic, recursive model of aetiology in sport injury

It was argued that while Gissane et al.'s (2001) cyclical operational model accounted for an athlete's return to sport following injury, it did not consider the potential adaptations that have taken place following events not just in the presence of injury, but also in the absence of injury that can continually change an individual's injury risk (Meeuwisse et al., 2007). Thus, the dynamic, recursive model of aetiology in sport injury aimed to incorporate the consequences of repeated participation in sport, both with and without injury (fig 2.8).

The authors suggested sport injury research should focus not just on the initial set of risk factors, but also look how these risk factors may change in the preceding cycles of participation and adopt suitable methodologies and analysis that can assess the cyclic nature of changing risk factors (Meeuwisse et al., 2007).

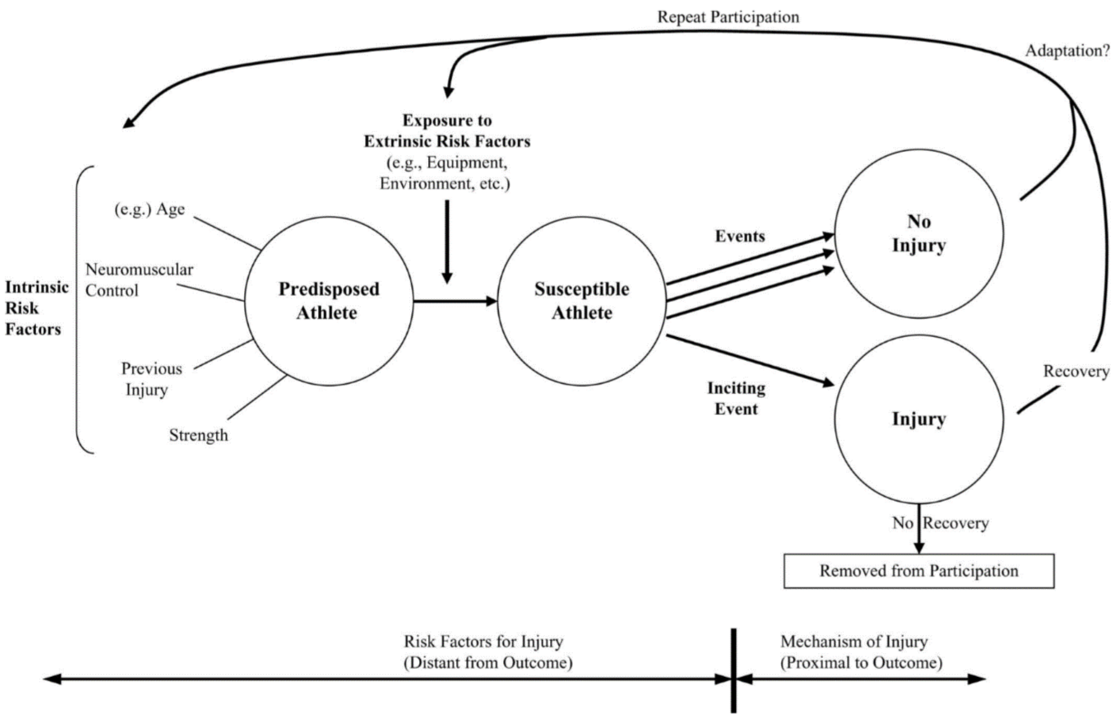

Figure 2.8: Dynamic, recursive model of aetiology in sport injury (Meeuwisse et al., 2007)

2.3.7. Workload-injury aetiology model

Although the previous models had developed to a point where the dynamic, recursive model of aetiology detailed the dynamic nature of injury risk, the cycles of participation and adaptation, it did not include a factor that had been strongly associated with injury risk: workload.

Workloads quantify the demands imposed on an athlete during matches and/or training (Gabbett et al., 2014). However, competition and training workloads are not a characteristic of the athlete or an aspect of the environment and so cannot be classified as internal or external risk factors. Instead, it has been proposed workloads should be considered as the 'vehicle' in which athletes are exposed to external risk factors and potential injury inciting events (Windt and Gabbett, 2017). Thus, the workload-injury aetiology model further developed the dynamic, recursive model of aetiology in sport injury by explicitly incorporating workloads (fig 2.9). Within this model, injury aetiology can be influenced by workload via increased exposure to inciting events and the positive (fitness) and negative (fatigue) individual adaptations from training. As such, an applied workload (via match or training) can modify the internal risk factors of an athlete, continually altering their injury predisposition (Windt and Gabbett, 2017).

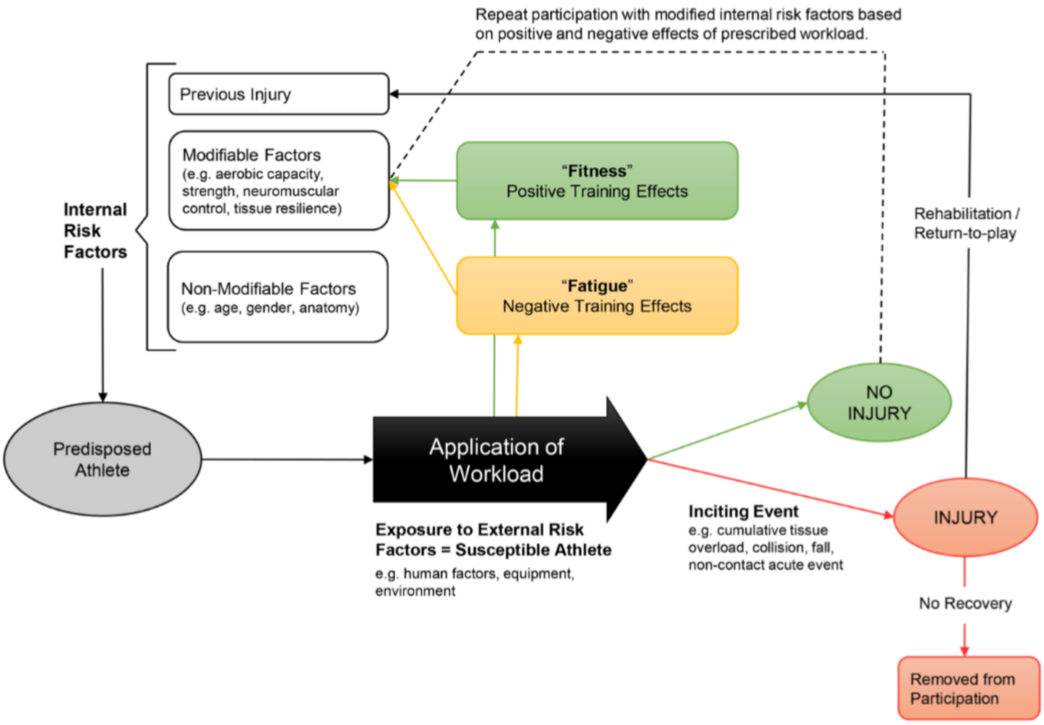

Figure 2.9: The workload-injury aetiology model (Windt and Gabbett, 2017)

2.3.8. Summary

The aetiology of sport injuries is complex. Several models have been developed that have increased understanding of injury risk factors at all stages of the process. Although the models do not always converge and fit together cohesively, they have provided several valuable frameworks that have and will continue to guide study design and analysis. Furthermore, the models continue to highlight the need to consider the changing nature of injury risk on an individual level as well as producing findings that can be practically applied. The models have demonstrated varying degrees of utility over time, but it's the 'sequence of prevention' model (van Mechelen et al., 1992), which lay the foundations many of the models were built on and is still useful and referenced today. Arguably, that original model remains relevant today, because it is a simple and eloquent framework that is easily understood. However, the most recent 'Team-sport Injury Prevention Cycle', with its consideration to provide a model that can be practically applied in a real-world context, provides the most useful injury prevention framework to guide the practice of science and medicine professionals.

2.4. Reporting sport injury data

In 2005, an international consensus statement was published that set recommended methods and definitions for injury surveillance in cricket (Orchard et al. 2005). It was the first sport to set out such guidelines and it was compiled with representatives from each test-playing nation where injury surveillance was being undertaken or proposed, which included Australia, England and Wales, South Africa, New Zealand, West Indies and India. The guidelines were deployed in several studies across the sport in the West Indies (Mansingh et al., 2005), India (Dhillon et al, 2012), New Zealand (Frost and Chalmers, 2014) and Australia (Orchard et al., 2006) to meet the aim of facilitating comparisons between settings and monitoring trends across the sport (Orchard et al., 2005). This section will provide an overview of the elements to be considered when reporting sport injury data.

2.4.1. Injury incidence

Injury incidence refers to the number of new injuries (new and/or recurrent) over a particular cricket game format and includes injuries that resulted in time being lost for a player or not.

The consensus statement defined a 'significant' 'match time-loss' cricket injury as:

> *"Any injury or other medical condition that either: 1) prevented a player from being fully available for selection in a major match, or 2) during a major match, caused a player to be unable to bat, bowl or keep wicket when required by either the rules or the team's captain. In addition, all time loss injuries were recorded, i.e. where a player is unavailable to fully train due to injury or illness, even if there was no training or match on those days."*
>
> (Orchard et al., 2005, pp. 1)

Although injury surveillance research was being conducted in the sport prior to the consensus statement, varying definitions and methods were deployed, meaning directly comparing published studies was difficult. An early study in England aimed to investigate the incidence, nature and site of acute injuries sustained during domestic competition (games within the national league and tournaments and not in international competition) in 54 professional cricketers in one county between 1985 – 1995 and presented an incidence rate of 57.4 injuries per 1,000 days of cricket played (Leary and White, 2000). The authors defined an injury as "the onset of pain or a disability resulting from either training for or playing cricket, which caused the player to seek medical attention" (Leary and White, 2000 pp. 145) and reported injuries per 1,000 days of cricket (a standalone unit at the time) and proportion for body part and playing position. Another such prospective cohort study included 436 cricketers from 11 provincial and national teams in South Africa for three seasons (Stretch, 2003). This study also reported injuries as percentage proportions for playing position, body area, game format, mechanism and injury type (e.g. soft tissue, joint, tendon) and similarly defined an injury as "any pain that prevented the player from completing that particular match, practice, or training session and caused the player to seek medical attention" (Stretch, 2003, pp. 251).

In the years following the publication of the consensus in 2005, a new shorter format of the game emerged and became an increasingly prominent part of the game; T20 cricket, where each team bats for

20 overs (unless all are out earlier) in one day. This led to Orchard et al. (2010) revisiting 11 seasons of Australia's injury surveillance data and incorporating T20 injuries into the final four seasons of that surveillance period. As this type of cricket had a shorter duration, the match injury incidence units (per 10,000 player hours) proposed in the original consensus over-estimated the incidence for this competition format. To enable more favourable comparison between the risk of the newer and shorter duration T20 cricket and the other game formats (Test and One-Day), a more standardised unit was proposed that reported match injury incidence in days (per 1,000 player days) as opposed to hours (Orchard et al., 2010).

This change in proposed injury incidence units in response to the increased prominence of T20 cricket was consolidated with its inclusion in the updated international consensus statement on injury surveillance in cricket (Orchard et al., 2016b). The consensus was revised not just due to the rise of T20 cricket, but to also include non-time-loss injuries (Mitchell and Hayen, 2005; Hodgson et al., 2007), which were excluded from the original consensus and as such contributed to the lack of universal uptake of the original definitions. While the original 'significant' cricket injury definition was retained and renamed specifically to 'match time-loss' (for when injuries cause the player to be unavailable on scheduled match days) and 'General time-loss' (refers to all time a player is unavailable such as training days, days off, off-season). Another injury definition was provided for injury surveillance at the elite level: 'Medical attention' injuries related to any health-related condition that required medical attention with the potential to affect cricket training or play and included time-loss and non-time-loss injuries.

In the updated consensus Orchard et al. (2016b) also suggested an annual unit of injuries per 100 players per year, which allowed for match, training, gradual and insidious onset injuries to be combined into one measurement. The time-period of a year was also suggested to replace the originally proposed 'season', to better reflect the evolving playing schedule that can encompass most of the year for major teams. The authors advised future publications to be clear on the exact methods used and report as many units as possible to provide flexibility for comparison. It was hoped the updated guidelines provided consistent definitions and measures that offered greater flexibility to researchers to choose methods that suited their study type that would enable comparison not just within cricket but also between different sports.

2.4.2. Injury prevalence

Prevalence is the proportion of a population found to be affected by a medical condition. It is presented as a percentage of players unavailable (for time loss injuries) or affected (for non-time loss injuries) and like incidence, the updated consensus suggests a few ways prevalence can be reported. One is 'match injury prevalence', calculated using the numerator of 'missed player games' and a denominator of number of games multiplied by the number of squad members. The other is 'annual' or 'general injury prevalence' where the numerator includes all days lost (e.g. match, training, off-days) and the denominator is the number of days for that given surveillance period (365 days for ‘annual injury prevalence’ or the number of days in a tournament for ‘general injury prevalence’) multiplied by the number of players in that squad or cohort (Orchard et al., 2016b).

Whether reporting actual days lost (through injury) or prevalence as a percentage of players unavailable at any given time, there has been less variation in previous cricket injury research on the units used for severity as there has been for incidence. Due to the varying amounts of cricket played in each country, prevalence remains a more standardised approach. However, there is still potential for differences in the prevalence used (such as ‘match’, ‘annual’ or ‘general injury prevalence’). For this reason, along with the guidance for incidence measures the updated consensus recommends future research clearly state the definitions of injury used and if possible, try and include as many types of incidence and prevalence units as possible to allow for flexibility in comparison (Orchard et al, 2016b).

In the wider sporting literature, it has been suggested incidence-based measures are best used in studies examining injury aetiology, prevention, and treatment that focuses on the number of athletes injured over a certain period. Conversely, prevalence-based measures can be used to descriptively reveal the proportion of players with injuries over a certain period, which can help identify treatment needs and player availability (Nielsen et al., 2017).

2.4.3. Training and match exposure

As the updated consensus provided definitions that would offer flexibility, several injury incidence measures related to training and match exposure have been suggested. ‘Match injury incidence’ refers to injuries occurring during major matches. The difficulty in reliably capturing ‘training injury incidence’ is acknowledged in the consensus. Some clubs have started capturing training workload for bowlers (number of deliveries bowled) and the consensus recommends using the same units as would be used for matches (deliveries bowled as opposed to overs bowled) so the suggested unit of bowling injuries per 10,000 deliveries bowled can be utilised (Orchard et al., 2016b).

In cricket all players are required to bat, but only some need to bowl. A player may not be fit to bowl but fit to bat, and as such available for selection. This complexity led the updated consensus to recommend avoiding ‘training time-loss’ definitions due to players regularly training in partial fashion, thus leaving the subjective classification of a ‘missed training session’ too difficult to determine on too many occasions (Orchard et al., 2016b). For this reason, the ‘general time-loss’ injury definition is comprised of a daily binary status of ‘considered fit to play a cricket match/not fit to play a cricket match’ regardless of whether there is a match scheduled or not. This aimed to remove any subjective ambiguity by providing a simple binary classification for a player to be assessed against.

There is no standard squad size or season between countries in cricket; a season can evolve into a 9-to-12 month schedule for major teams (particularly at international level). As such, a ‘seasonal and yearly injury incidence' measure was suggested in the updated consensus (Orchard et al., 2016b). This enables match, training and gradual onset injuries to be combined and used in one measurement, with injuries reported per squad per season. Due to the lack of a typical squad size, for simplicity Orchard et al. (2016b) recommended calculating seasonal/yearly injury incidence per 100 players per year.

2.4.4. Injury classification systems

Coding of injuries is an important part of injury surveillance to facilitate the retrieval of records for future analysis and to enable the collation of diagnoses into common groups to identify trends in injury incidence and prevalence (Orchard et al., 2010). This is particularly pertinent in relation to Van Mechelen et al.'s (1992) 'sequence of prevention' model, with the first stage to establish the extent of the problem. Such coding provides a consistent, structured approach to data collection that can facilitate comparison between studies (Rae and Orchard., 2007).

The Orchard Sports Injury Classification System (OSICS) has been widely used in sport and, most importantly in the context of this thesis, is the injury classification system that been used in previous cricket epidemiology research and the preferred classification system of the England and Wales Cricket Board for ongoing surveillance of elite cricketers in the United Kingdom (Hammond et al., 2009). The OSCIS has become the one of the world's most widely used injury coding systems in sports medicine. The freely-available system has been used in soccer, Australian football, tennis, rugby union and cricket (Orchard et al., 2010). Originally published in 1993 (Orchard, 1993), the classification system used three digits, one to define the body location, the second and third related to the pathology of the injury.

The OSCIC system's reliability was tested in 2005 through comparison with another coding system (used in sports medicine but developed in health research), The International classification of diseases 10-Australian modification (ICD-10-AM). Ten sports physicians volunteered to code one of ten different lists of thirty sports medicine diagnoses according to ICD-10-AM and OSICS (*version 8*) in random order (Rae et al., 2005). These results were then compared with the same three hundred diagnoses coded twice more by 'expert' coders from each system. The average pairwise agreement between the groups was higher for OSICS-8 than ICD-10-AM (57.2% to 35.3% respectively) and OSCICs-8 was 23.5 minutes quicker to complete. However, the authors rightly highlighted agreement levels for both systems were lower than expected, with improvements recommended to both systems to improve their reliability for use within sports medicine (Rae et al., 2005).

This led to the development of OSICS-10, which included a four-character system to further describe the injury pathology (Rae and Orchard, 2007). The OSICS-10 was found to be a more encompassing system, when eight clinicians coded a list of 20 diagnoses with the OSCICS-10 and OSICS-8 and all diagnoses could be assigned an appropriate OSICS-10 code compared to 87% with OSICS-8 (Hammond et al., 2009). An overall moderate level of inter-rater agreement was found (Fleiss' Kappa (k) = 0.56) with further revisions suggested to address a proposed lack of detail in some of the codes.

Some minor modifications to include more codes to further describe pathology were included in the most recent updated version; OSICS-10.1 (Orchard et al., 2010). The authors commented the updated OSICS-10.1 is very similar to OSCIS-10 and as such did not require a full re-write.

2.4.5. Subsequent injuries

Subsequent injuries refer to any new (different location, local – same location, different type) and recurrent (same location and same type) injury that occurs after an initial injury (Hamilton et al., 2011; Finch et al., 2017; Toohey et al., 2018). With previous injury shown to be a significant risk factor for future injury (Kucera et al, 2005; Hägglund et al., 2006; Orchard et al., 2015; Rossi et al., 2018), understanding subsequent injuries has been critical for sports injury epidemiology. As such the Subsequent Injury Categorisation (SIC) Model was developed (Finch & Cook, 2014) and later expanded (Toohey et al., 2018) to provide a more objective framework for accurate categorisation of subsequent sport injuries and the quantification of injury recurrence patterns. The codes and definitions are shown in table 2.1.

Table 2.1: Subsequent injury categorisation (SIC) codes and definitions (Finch and Cook. 2014).

Subsequent injury type by body area and nature (overarching category)	Code	Definition
No injury	1	No injury, for statistical purposes only
Exact same injury in terms of body site and nature	2	Same type, same side, same body area as a fully recovered index injury, and related to an index injury
	3	Acute onset exacerbation or reinjury before full recovery, related to an index injury
	4	Continual or sporadic experiences of pain or other physical discomfort - related to an index injury
	5	Continual or sporadic experiences of pain or other physical discomfort - not related to an index injury
	6	Same type and same body area but not related to an index injury
Injury to same body site but different nature	7	Occurrence related to an index injury
	8	Occurrence not related to an index injury
Injury to different body part (irrespective of nature)	9	Occurrence related to an index injury
	10	Occurrence not related to an index injury

There is little evidence for the reliability of the SIC model. However, one study did test the initial SIC model (Finch and Cook, 2014) in cricket and rugby union for one international team (Sri Lanka and Wales respectively) between 2011 and 2014 (Moore et al., 2018). Moderate agreement (Cohen kappa ≥0.60) was observed for clinicians working both with and not with the team in both sports. Overall, 51% of the subsequent injuries in cricket were recorded as ‘new’ as opposed to ‘recurrent’, with more subsequent new injuries occurring in rugby (67%). The greatest level of SIC coding agreement was between two clinicians within the same team who had the most direct clinical knowledge of the injuries and may be more aware of the ongoing management of injuries compared to the non-clinicians (Moore et al., 2018). This was aptly demonstrated by clinicians applying SIC code 4 to new injuries, with the non-clinician often using SIC code 2 for the same injury. What’s more, the inclusion of non-time loss injuries appeared to affect the level of agreement, with a better agreement between clinicians, but lower agreement between non-team clinician and sports scientist. This was particularly pertinent to cricket, where a higher proportion of non-time loss injuries were reported (Moore et al., 2018). The authors suggested practitioners with limited clinical knowledge should group data with the overarching categorisations (table 2.1) when applying the SIC model.

2.4.6. Statistical approaches

Injuries occur because of complex and non-linear interactions amongst multiple variables, and it has been proposed that the conventional reductionist statistical approaches often used to study them are unlikely to fully capture their dynamic and multiplex nature (Ruddy et al., 2019). As such, it has been suggested that research implementing reductionist approaches should be used to inform and implement complex approaches to identify injury risk and/or predict injuries (Ruddy et al., 2019). Complex statistical approaches include (but are not limited to) algorithmic models such as generalised mixed effect models and supervised learning techniques, which are a type of machine learning (with the most commonly used techniques being decision tree and random forest classifiers) able to account for the complex, nonlinear interactions between injury risk factors (Bittencourt et al., 2016).

Supervised learning is when a ‘training’ data set that has a known outcome variable (in this case an injury or not) is used to identify pattens and predict the same outcome variable in an unknown independent ‘testing’ data set (Han & Kamber, 2006). One study in Australian football had limited success with supervised learning techniques, demonstrating similar predictive power to a random coin toss (Ruddy et al., 2017). The authors suggested a larger amount of training data might improve the ability of the algorithms to identify patterns and make more meaningful predictions. A big limitation when using complex statistical approaches to model injury risk is the amount of data required for these methodologies to make meaningful inferences (Carey et al., 2018). The Australian football study was focused on predicting hamstring strain injuries with data collected at the beginning of pre-season, with the noted unknown being whether more frequent measures of the variables would have improved model performance (Ruddy et al., 2019). However, a model developed in Spanish soccer has demonstrated better predictive power (also focused on hamstring strain injuries) with measures also only taken pre-season, although this study had a smaller sample and the authors acknowledged the complexity of the final model that involved 10 different classifiers and 66 predictors (Ayala et al., 2019). The authors also highlight the need to ensure standardisation in the data collection of any measures included in any potential model, which can be helped by setting a rigorous protocol for each measure (Ayala et al., 2019). Another model with reasonable predictive power was developed in professional soccer, with the study finding only 3 variables were selected for the best performing classifier, out of 42 predictor variables included in the models (Rossi et al., 2017).

Risk prediction tools like these, are mathematical models that aim to use multivariable factors to assess the risk of a future event (in this case injury) of occurring, usually incorporating both causal and non-causal factors to improve predictive performance. When developing risk prediction models, the

Transparent Reporting of a multivariable prediction model for Individual Prognosis or Diagnosis (TRIPOD) guidelines should be followed to ensure the usefulness of the prediction models studied can be adequately assessed (Grant et al., 2018). TRIPOD recommendations were developed in 2015 (Moons et al., 2015) and designed to improve the quality of risk prediction model research. To date, such models have never been applied to assess nonlinear interactions between injury risk factors in cricket.

2.4.7. Summary

There are several considerations with reporting sport injury data, with proposed guidelines for injury surveillance in cricket (Orchard et al., 2016b). The consensus suggested including both new and recurrent injuries in injury incidence and prevalence measures and stated any future research should try and report as many definitions as possible (to enable comparison) stating clearly in their methodology, which measures used and how they have been calculated. The use of complex statistical approaches in sport injury research may benefit the subject area, not necessarily in predicting injury (with previous research showing such approaches have poor to reasonable predictive power in this context) but in identifying risk factors important in predicting injury.

2.5. Risk factors for injury

A number of factors can influence an individual's injury risk. Such factors can be intrinsic (to the athlete) or extrinsic (environmental) as outlined in the various sport injury models in section 2.3. This section will provide an overview of these risk factors, starting with intrinsic factors, followed by extrinsic factors.

Intrinsic risk factors

2.5.1. Age

Age has been shown to be a significant risk factor for injury in other sports, with (to name a few) a higher injury rate associated with increased age in New Zealand rugby union (Quarrie et al., 2001), indoor soccer (Lindenfeld et al., 1994) and hamstring and calf strains (specifically) in Australian football (Orchard, 2001). A systematic review and meta-analysis into specific risk factors of hamstring strain injury in sport found older age (standardised mean difference = 1.6, P = 0.002) to be one of the strongest risk factors for hamstring strain injury, from the 78 studies included in the review (Green et al., 2020). There is, however, currently a lack of conclusive evidence in cricket to ascertain the extent to which age is a risk factor in this sport. The cricket injury epidemiology studies mentioned previously that have deployed methods suggested in the international consensus, have focused on injury incidence and prevalence for position, game format and body part.

Given the identified increased risk of injury for fast bowlers, a study retrospectively analysed fourteen years (1998-2012 inclusive) of injury surveillance data for fast bowlers in Australia specifically to explore age as a potential risk factor to the injuries sustained (Blanch et al., 2014). Younger bowlers (less than 22 years old) were found to be 3.7-6.7 times more likely to suffer a bony injury than all other age groups. Along with the older age grouping (over 31 years), the younger (less than 22) age grouping were 1.8-3.7 times more likely to suffer a joint injury that other three age groupings (22-25, 25 to 28 and 28 to 31 years) between them. Tendon injury incidence gradually increased with age and the highest rates were found in the over 31 age group (Blanch et al., 2014). However, the authors acknowledged the tendon finding could be the result of ankle impingement being classified as a tendon injury as opposed to any age differences. Furthermore, although the overall sample number (*n* = 215) and total number of injuries (*n* = 563) were provided, the number of players and injuries sustained in each age group was not supplied, which means confidence intervals cannot be calculated, placing doubt on how assured we can be with the study findings. No differences were found between age groups for injury severity. While this study shows how injury profiles may differ with different ages, in part due to skeletal maturity and training age capability, it is still not clear if the injuries sustained to each grouping are proportionate to the number of players registered and participating in injury surveillance for each age group.

There is a theoretical basis for any suggested differences in injury risk for age. Cumulative load theory states that biological tissues, like any other physical material are subject to wear and tear with repeated load application resulting in cumulative fatigue, which in turn reduces a tissues stress-bearing capacity (Kumar, 1990). This would imply potential increased injury risk for older players, but such increased exposure could also serve to build some resilience. As the dynamic, recursive model of aetiology in sport injury (Meeuwisse et al., 2007) proposes, the player is an active part in the cyclic nature of ever-changing risk factors with their intrinsic risk factors continually adapting and evolving.

Although age injury risk differences have theoretical underpinning and evidence from other sports to support age as a potential risk factor, stronger empirical evidence is needed specifically within the context of cricket. Some initial research exists, but future research needs to be clearer on the proportion of players injured from the number of players available for each grouping.

2.5.2. Sex

Along with age, sex is another internal predisposing injury risk factor proposed by Meeuwisse's (1994) multifactorial model of aetiology as outlined in section 2.3.3. The development of the women's game in cricket over recent years, which has included the introduction of the semi-professional Kia Women's Super League competition in 2016, has increased the relevance of this risk factor within cricket, however there has been little cricket specific research in this area (Munro & Christie, 2018).

One cricket study that did compare sex differences on musculoskeletal profile of the lumbar spine and hip regions in fast bowlers, found females had significantly more bilateral hip extension range of movement than the male bowlers (Stuelcken et al., 2008). However, the study included unequal sample sizes of 26 females and eight males as well as some of female participants in the sample having a history of low back pain (14 females compared to zero males reporting back pain). There was also differing competitive levels in the sample, with all but one of the females identified as 'elite' by the national coach and all male bowlers' were members of representative squads in the Australian Capital Territory and as such considered 'non-elite'. The sampling bias in this study undermines the validity of any gender differences supposedly found.

Another cricket study compared biomechanical characteristics between male and female elite fast bowlers and found significant differences between ball release speed, the kinematics at back foot contact, front foot contact, and ball release and the timings between these instances (Felton et al., 2019). As a consequence of these differences in linear momentum at front foot contact, the females were found to typically adopt a bowling technique that was more akin to throwing, where ball release speed was contributed to by both the whole body angular momentum and large rotator muscles used to rotate the pelvis and torso segments about the longitudinal axis. However, the extent to which both groups (males and females) can be adequately compared is uncertain. Although both the males and females included in the sample are considered elite, with the recent and emerging professionalisation of the women's game, it is likely the male bowlers have substantially more experience and time within a professional environment.

It may not be then that sex is an injury risk factor, but should be studied independently, with the injury profile for the women's game needing to be distinctly understood. In Rugby-7s different injury profiles were found between the men's and women's game, however it is important to consider injuries for female players included mixed competition levels (amateur to elite) and not just international level as reported for the male injury rate (Mat et al., 2016)

There has been a noted paucity of research in women's cricket in Munro and Chrisite's (2018) review. Initial research into injury profiles in elite women's cricket have found high incidence of shoulder and fielding (which requires a lot of throwing) injuries. Shoulder injuries were found to have the greatest incidence, particularly from throwing in England and Wales T20 cricket (Warren et al., 2019) with shoulder injuries the second highest body region injured in a study on elite female cricketers in Australia (Perera et al., 2019). In both studies, fielding was the activity in matches and training that resulted in the most injuries. A recent systematic review conducted on the epidemiology of injuries in women playing competitive team bat-or-stick sports concluded that injury prevention in this area is indeed a novel and emerging field (Perera et al., 2017). Of the 37 studies that satisfied the inclusion criteria, only five had low risk of bias. The authors similarly called for enhancements to injury data collection for the women's game, to inform developments in evidence-based injury prevention interventions specific to the women's game.

2.5.3. Physical characteristics

All sports injury models start with a predisposed athlete who has several modifiable risk factors such as strength, neuromuscular control and general anatomy. Considering differential fatigue theory, muscles are susceptible to fatigue at varying rates (Kumar and Narayan, 1998) and as such, the amount of strength and conditioning a player undertakes can influence their injury risk. This has been shown to be particularly pertinent for repeatedly performed techniques and consequently, it would be reasonable to assume anyone undertaking such repeated techniques (such as batting and bowling in cricket) would benefit from developing the strength of the muscles activated during such actions.

A common theme with cricket research is a focus on fast bowlers, because of the significant increased risk of injury for this position. Due to the high incidence of lower back pain in bowlers, the abdominal muscles involved in trunk rotation have been particularly explored. Asymmetry of abdominal muscle thickness has been found in fast bowlers because of the asymmetrical biomechanics of the technique (Engstrom et al., 2007; Hides et al., 2008). Contrary to non-sporting populations, however, such asymmetry has been found to be protective rather than provocative for lower back pain (Gray et al., 2016; Martin et al., 2017).

Another proposed indicator of heightened injury risk in bowlers is performance in the single leg and star excursion balance test at the start of season. A longitudinal observational study in South Africa found those who performed better in these tests did not sustain an injury during the cricket season, out of the thirty-two injury free male participants (aged 18 to 26 years) under surveillance (Olivier et al., 2015). However, performance on the lumbo-pelvic movement control tests did not distinguish bowlers who sustained an injury and those who did not. Any associations are speculative due to results being based on a comparison of means conducted between two groups in a small sample over a single season.

A review that looked to identify possible mechanisms for shoulder injuries in cricketers highlighted the challenge in determining from previous studies if some of the proposed mechanisms (scapula dyskinesia and abnormalities in the musculature surrounding the cuff) were a cause or effect of shoulder injury (Arora et al., 2015). Further research is needed to investigate this as well as to increase understanding on the role of muscles surrounding the cuff in the shoulders of injured and non-injured cricketers and the potential impact of individual differences within this. While there is a reasonable theoretical base to suggest an individual’s physical characteristics will influence their injury risk, more research is needed in cricket to ascertain the specific injury risk from an individual’s physical characteristics that can inform suitable prevention strategies and guide specific injury pre-rehabilitation prescriptions.

2.5.4. Previous injury

Previous injury has been shown to be a significant risk factor for future injury, with more previous injuries seemingly leading to greater injury risk. A systematic review and meta-analysis of 78 studies investigating risk factors of hamstring strain injury across various sports found a history of hamstring strain injuries (relative risk [RR] = 2.7, $P<0.001$) was one of the strongest risk factors (alongside older age) for hamstring strain injury (Green et al., 2020).

Prospective cohort studies in soccer have found players with a previous injury had a threefold increased risk of injury when compared with players who had no previous injuries (Kucera et al, 2005; Hägglund et al., 2006). Another soccer study that aimed to deploy machine learning to predict injury found previous injury to be one of just three crucial predictors of injury risk (Rossi et al., 2018). This was especially true in the early days after returning from injury, with 58% of subsequent injuries sustained within three days of training after returning from injury.

In cricket, the risk of developing a tendon injury in the next 21 days was found to nearly double (Odds ratio [OR] = 1.85, 95% CI 1.33 to 2.55) if there was a previous injury in the same season (Orchard et al., 2015). The authors suggested this could be as a result of a previous injury in the same season resulting in a period of zero workload when the player was injured, with workload (overs bowled) also found to be a significant risk factor injury in the study. Such an association with workload would be explained by Windt and Gabbett's (2016) workload-injury aetiology model and the theory that 'you need to load to withstand load' (Reeves et al., 2005). But this may also in part be explained by Meeuwisse et al.'s (2007) dynamic, recursive model of aetiology in sport injury that proposed the adaptations that may be necessary after an injury can alter a player's intrinsic risk factors and continually change an individual's injury risk. This model has been empirically supported by Fulton et al.'s (2014) systematic review, which examined the association between previous injury and subsequent injury risk and found post-injury changes were present in a player's strength, proprioception and kinematics, which can then alter motor control and function that in turn raise injury risk.

In cricketers, this potential post-injury adaptation could be the explanation for the strong association found in risk of calf strain and previous lumbar stress fracture injury history in first class pace bowlers over 11 years of injury surveillance in Australia (Orchard et al., 2010). The authors suggested the bony hypertrophy resulting from the healing of lumbar stress fractures may lead to subsequent lumbar nerve root impingement and consequently lower limb muscle strains may be more likely to occur. However, there were several confounding variables (such as bowling speed, severity of previous lumbar stress fracture, technique, anthropometric characteristics) that may be responsible for these findings. What's more, weak or no associations were found between lumbar stress fracture history and other lower limb injuries, such as groin, hamstring and quadriceps strain, which may allude to the findings being more sample-specific, thus limiting the generalisability of the findings.

Limitations aside, there is still an association that warrants further investigation in cricket and with such a strong theoretical basis for the connection and the evidence from other sports, previous injuries must be considered a significant risk factor for future injuries that can be used to identify and manage players at higher risk.

Extrinsic risk factors

2.5.5. Workload

Workload quantifies the demands imposed on an athlete during matches and/or training (Gabbett et al., 2014) and has been shown to be associated with injury risk. Compared to other team sports, cricket is a complex as it is effectively an individual sport within a team context (Christie et al., 2020). There is a noted paucity of literature on workload monitoring in team sports such as cricket (Christie et al., 2020). The limited previous cricket-related workload research has focussed on fast bowlers (as it is the position with the highest injury incidence), with great variations found in player workload (Orchard et al., 2010).

A method often deployed in these studies to monitor workload is the 'acute:chronic workload ratio' (ACWR). With the ACWR, workload performed in a week (acute workload) is examined relative to a 4-week average workload (average calculated from the acute workload to determine the 'chronic' workload). This provides an index that can be used to indicate whether a player's recent (acute) workload is greater, less than or equal to the player workload built up over the preceding 4-week chronic period (Hulin et al., 2016). In cricket, as the majority of workload studies have focused on fast bowlers, the ACWR is commonly calculated from the number of balls bowled (with six balls equating to one 'over').

Initial research on the association between workload and injury found a consistent relationship between high bowling workload and injury, with injury risk higher for fast bowlers with sessional, weekly and monthly bowling workloads above the group mean, especially when this high workload was consistent and sustained (Dennis et al., 2004). However, it was not just high workload that was found to be associated with injury risk; there seemed to be a dual fast bowling workload threshold beyond which injury risk increased, whether this was maintaining a workload that was too high or too low and infrequent (Dennis et al., 2003). Hulin et al. (2014) conducted a prospective cohort study with 28 senior fast bowlers over a 6-year period and found it was not just high or low workloads that were associated with increased injury risk, but more 'spikes' in acute (1-week) workload. It was suggested that higher workloads over a chronic period (4-week average) can result in positive physical adaptations, which in turn can minimise the influence of fatigue and thus reduce injury risk (Hulin et al., 2014). These findings were further validated by Orchard et al. al. (2015) who found fast bowlers who bowled more than 50 overs in a five-day period had a significant increase (RR = 1.54, 95% CI 1.04 to 2.29) in injury over the next month compared to those who bowled fifty overs or less. Conversely, those who had a higher workload over a more chronic period, bowling more than 100 overs in 17 days had a non-significant increase (RR = 1.78, 95% CI 0.90 to 3.50) in injury the next month (Orchard et al., 2015).

However, a consideration for both Hulin et al. (2014) and Orchard et al. (2015) is that the injury risk is calculated from an aggregation across the sample and did not account for individual variance in load response. While the studies were conducted over a long time period (Hulin et al. (2014) for 6 years and Orchard et al., 2015 for 15 years), enabling the identification of trends over time that produce more robust findings, there is a potential lack of generalisability to the outcome that fifty overs in a five-day period can result in increased injury risk with certain players having higher or lower thresholds.

This notion of considering individual differences in the acute:chronic workload-injury relationship has been empirically supported by Warren et al. (2018), who also found high ACRW of 109-142% (RR = 1.46, 90% CI 0.93 to 2.29) and >= 142% (RR = 1.66, 90% CI 1.06 to 2.59) were associated with injury in 29 male fast bowlers on the England and Wales Cricket Board (ECB) national development programme. High chronic (4-week average) workload of greater than 83 balls were found to attenuate the influence of high ACWR on injury risk (RR = 0.35, 90% CI 0.17 to 0.74). What's more, significant individual differences were also evident, leading the authors to suggest not only should fast bowler workloads be monitored to avoid rapid fluctuations, but any decisions around workloads should be based on individual and not cohort aggregated data (Warren et al., 2018). However, an important consideration with Warren et al.'s (2018) study is the age of the sample is lower (age range 15-18) than what has been used in previously published research and with differing injury risk associated with different ages, caution needs to be exercised with the extent these findings can be generalised and compared to cohorts of different ages.

While ACWR has been widely deployed, the use of rolling-averages has been criticised for failing to account for the decaying nature of fitness and fatigue effects over time (Hawley, 2002). Recent systematic reviews investigating the association between ACWR and injury risk in professional sport found that although the a number of studies suggest athletes are at a greater risk of sustaining an injury when the ACWR is higher relative to lower/moderate ACWR, the heterogenous methodological approaches limit the strength of the findings (Andrade et al., 2020; Maupin et al., 2020). Generally, it has been determined there is poor evidence to support ACWR as a risk factor for injury (Coyne et al., 2018; Impellizzeri et al., 2019), and a number of methodological concerns with this metric have been raised (Wang et al., 2020). As opposed to the rolling averages often used in calculating 'acute' and 'chronic' workloads, Williams et al. (2017) proposed the use of 'exponentially-weighted moving averages' (EWMA), which assign a decreasing weighting for each older load value. This has recently been tested in Australian football where the EWMA model was directly compared against the rolling-average model and while both models demonstrated large spikes in workload were associated with increased injury risk, the EWMA model was more sensitive to detecting increases in injury risk with higher ACWR (Murray et al., 2017).

A systematic review (that included 27 studies) on the association between ACWR and injury risk proposed the use of EWMA in ACWR may result in a more sensitive measure to the traditionally used rolling average (Maupin et al., 2020). Research has also started testing alternatives to the traditional ACWR for workload monitoring in cricket, with a 9-day acute and 42-day chronic load found to be the best-fitting predictor variable for injury risk when a variety of different ACWR combinations were tested (Tysoe et al., 2020). The study also found the best model fit combined the 9:42 -day ACWR with an exponentially-weighted 7-day differential load. The 7-day differential load measure represents the smoothed rate of change in load from one week to the next, and thus captures 'spikes' in acute loads, whilst mitigating methodological issues associated with the use of ACWR (Hawley, 2002).

2.5.6. Game format

Following the original consensus statement on injury surveillance in cricket (Orchard et al., 2005), three papers (Mansingh et al., 2005; Orchard et al., 2006; Frost & Chalmers, 2014) deployed standardised units for reporting match injury incidence (per 10,000 players hours). As a result, it was possible to compare incidence rates between game formats from different countries to enable identification of any trends over time. The three papers reported match injury incidence for both domestic and international competitions and these data are presented in table 2.2. While two of the three studies reported an overall or mean match incidence (Frost and Chalmers, 2014; Mansingh et al., 2005 respectively), Orchard et al. (2006) presented incidence for each year of the surveillance period and as such, a mean has been calculated.

The injury incidence rates across the three studies were not dramatically different, except for One-Day International incidence in New Zealand seemingly being considerably higher (73.1 per 10,000 players hours) than what was reported for the West Indies (40.6 per 10,000 players hours). However, as Orchard et al. (2006) acknowledged, caution would have to be exercised in declaring West Indies had different injury rates to New Zealand and Australia, due to the small number of injuries recorded (*n* = 50 time loss injuries) during the short study period of Mansingh et al.'s (2005) study.

Limitations aside, there are some differences that emerge. One-Day cricket was associated with a higher incidence rate than Test cricket, which may be due to the increased intensity of the shorter format (Peterson et al., 2011). There is also increased injury incidence at International level (potentially due to the increase in intensity and performance/competition at this level), for both formats of the game. However, due to the period the injury surveillance was conducted for the Mansingh et al. (2005) and Orchard et al. (2006) papers, they did not include incidence for a form of cricket that would become increasingly prominent from 2005; Twenty20 (T20). As previously outlined, due to the shorter duration of the game, the original proposed match injury incidence units (per 10,000 player hours) produced overly high incidence for this competition format and as such it was not comparable to the other longer forms of the game (Orchard et al., 2010). Although Orchard et al. (2010) suggested the increased injury

Table 2.2: Mean cricket match injury incidence (per 10,000 player hours) for international studies

			Domestic		International	
Authors	Country	Time surveyed	Test incidence	One-Day incidence	Test incidence	One-Day incidence
Mansingh et al. (2005)	West Indies	Jun 2003 to Dec 2004	13.9	25.4	48.7	40.6
Orchard et al. (2006)	Australia	1995 - 2005	27.3	38.5	31.4	59.8
Frost and Chalmers (2014)	New Zealand	2002 - 2008	14.1	36.2	30.1	73.1

rates observed during that injury surveillance period (1998-2009) may be because of the increased amount of T20 cricket. Orchard et al. (2016a) with Cricket Australia used the updated injury incidence units (per 1,000 days of play as outlined in Orchard et al.'s (2016b) updated consensus statement) to compare risk across all 3 competition formats for 10 seasons (from 2006-2016 inclusive). The highest incidence rate remained with One-Day 50 over cricket, with an average of 271 (for domestic cricket) and 263 (for international cricket) injuries per 1,000 days of play. T20 cricket had the second highest average match incidence with 194 injuries per 1,000 days of play. First-Class Test cricket had the lowest risk of all the competition formats with an average 117 and 118 injuries per 1,000 days of play for domestic and international cricket, respectively (Orchard et al., 2016a). However, it is important to highlight the authors combined both international and domestic injury rates for T20 cricket, but split them for the other, longer forms of the game. This was due to the low number of international T20 matches for certain seasons but remains an important consideration when comparing the different competition formats in this study, as grouping domestic and international incidence rates means the overall findings may not be representative of other T20 cricket playing nations.

Although T20 and One-Day cricket has been found to be more intense, with approximately 50-100% more sprints per hour compared to multi-day Test cricket, multi-day cricket has a greater overall physical load, with the longer format resulting in 16-130% more sprinting per day (Peterson et al., 2010). Soomro et al. (2018) conducted a systematic review on 15 articles for cricket injury epidemiology in the twenty-first century and found there was not enough evidence to conclude T20 cricket has increased injury rates. However, a limitation of their review was the use of the original injury incidence unit (per 10,000 player hours) despite the issues outlined by Orchard et al. (2010) and their unsuitability for comparing competition formats, where the unit can over-estimate injuries for shorter formats.

One injury unit that has been consistently used in previous research and does allow for comparison across game formats that may provide additional insight into what format carries the most risk is prevalence (for match days only). However, the challenge remains when comparing prevalence rates from different international studies where different quantities of cricket are played in different conditions over different time periods. Mansingh et al. (2005) and Orchard et al. (2006) reported prevalence rates for Test and One-Day games for domestic and international competitions (table 2.3) with no great differences between the figures. Overall prevalence figures, which included Test, One-Day and T20 injuries, were presented by Orchard et al. (2010) and Frost and Chalmers (2014) for Australia and New Zealand respectively (table 2.4). No substantial differences were evident between the rates, though prevalence was typically higher in international settings.

Table 2.3: Prevalence for Domestic and International Test and One-Day format from West Indies and Australia

			Domestic		**International**	
Authors	Country	Time surveyed	Test prevalence	One-Day prevalence	Test prevalence	One-Day prevalence
Mansingh et al. (2005)	West Indies	Jun 2003 - Dec 2004	(Not reported)	(Not reported)	11.3%	8.1%
Orchard et al. (2006)	Australia	Oct 1995 - Mar 2005	8.2%	8.5%	7.5%	9.4%

Table 2.4: Prevalence for overall Domestic and International cricket for Australia and New Zealand

			Domestic	**International**
Authors	Country	Time surveyed	Overall prevalence (Test, One-Day and T20)	Overall prevalence (Test, One-Day and T20)
Orchard et al. (2010)	Australia	Oct 1998 - Apr 2009	11.5%	12.8%
Frost and Chalmers (2014)	New Zealand	Apr 2002 - Apr 2008	9.7%	12.0%

While overall prevalence is greater for injuries sustained at the highest international level, the obvious restriction is the ability to compare across all three of the prominent formats to ascertain which one holds the highest risk for injury. The only study to do this over a reasonable time-period is Orchard et al.'s (2016a) injury surveillance of elite male cricket injuries, which included all domestic and international competitions in Australia over ten seasons from October 2006 to April 2016 (table 2.5).

Table 2.5: Average prevalence for Australia Domestic and International cricket

			Domestic		International		Overall (Domestic and International)
Authors	Country	Time surveyed	One-Day	Test	One-Day	Test	T20
Orchard et al. (2016a)	Australia	Oct 2006 - Apr 2016	12.3%	12.2%	14.9%	13.6%	11.6%

Similar to the incidence rates, injuries in One-Day cricket have the highest prevalence, particularly at International level. Although T20 had the second highest incidence out of the three formats, it had similar prevalence but more research is needed to validate these findings due to the lack of published literature on T20 cricket.

Generally, it seems it can be expected that approximately 12% of players will be unavailable for matches over the course of a season due to injury for any format (slightly higher at international level). Based on previous research, One-Day cricket seems to be the format that holds the highest risk, followed by T20 for incidence, due to the increased intensity of these formats (Peterson et al., 2011). Injuries in test cricket result in the highest prevalence but this could be due to substantially more injuries from the increased exposure of this format compared to the other, shorter formats.

2.5.7. Level of play

Injury rates have been found to increase with level of play at junior community (Finch et al., 2010) and elite level, where consistently higher injury incidence and prevalence has been found at international compared to domestic level (Mansingh et al., 2005; Orchard et al., 2006; Orchard et al., 2010; Frost and Chalmers. 2014; Orchard et al., 2016a). This has been found for both Test and One-Day cricket competitions (T20 cricket rates have combined domestic and international competitions), apart from prevalence rates for Test cricket, which were found to be marginally lower for international level (7.5%) compared to domestic Test competition (8.2%).

The majority of cricket injury research has been conducted at the elite level, but there have been some studies that have explored non-elite levels (e.g. youth and recreational) of the game. Comparing results and identifying consistent trends across research at these levels can be particularly challenging due to the lack of consistency in data collection methods, injury definitions, provision and units used in analysis. However, the results are still of interest and should guide further research.

Understandably, the trends that have emerged from research at the elite level do not seem to be mirrored at the lower levels of the game. While research at the elite level has consistently found fast bowlers to be at the highest risk of injury, a prospective cohort study that conducted injury surveillance on under 12 (n = 88), under 14 (n = 203) and under 16 (n = 120) Australian junior community-level club cricketeers over the course of a season found injuries occurred as frequently to fielders and batters as they did to bowlers (Finch et al, 2010). This finding is supported in junior cricketers perceived injury risk with junior players under 12 and 14 accurately reporting higher injury risk perceptions for both batting and fielding than players under 16, who conversely had higher perception of injury risk associated with bowling (White et al., 2011). However, the similarities between the two studies may be more reflective of the same sample being used for both studies [within the Ballarat Cricket Association (BCA) in Victoria Australia at the start and over the 2007/2008 season]. That said, the injury risk perception survey was administered at the start of the season, with the injuries then recorded prospectively for that season. The accurate perceptions reported by the junior players could simply be formed from experience of previous seasons and may not be generalisable to junior cricket in other countries and even clubs.

There is evidently greater risk associated with playing at a higher competition level, but more needs to be done to better understand the injury risks and how they may vary at the lower levels of the game.

2.5.8. Playing position

Fast bowlers have consistently been found to have the highest risk of injury compared to any other position at a senior elite level (Stretch 2003; Orchard et al. 2006; Mansingh et al, 2005; Frost and Chalmers, 2014; Orchard et al, 2016a). An early study that provided initial evidence for this notion was conducted before the international consensus on injury surveillance was published and injury surveillance programmes became established. In South Africa, thirty-six physiotherapists and thirteen doctors working with the eleven provincial teams in South Africa completed a questionnaire on each cricketer who presented an injury during the three seasons under surveillance (Stretch, 2003). Of the 436 cricketers who sustained 812 injuries, fast bowlers were the most injured, accounting for 33.3% of injuries, followed by all-rounders (29.9%) and batsmen (24.2%). However, this contradicted an earlier study conducted in England, which recorded injuries sustained by cricketers at one county club over 10 years and found no significant difference in injury incidence among player positions from the 990 injuries recorded (Leary and White, 2000). Though as previously documented, the challenge with the findings from these early (pre-consensus) studies is the lack of consistent methodologies and definitions, which makes it impossible to directly compare these early published studies and as such any findings should be treated tentatively.

As hamstring injuries have been consistently high for injury incidence, the risk factors for this injury were explored in Australian male professional cricket players (Orchard et al., 2017). Fast bowlers had the highest incidence of hamstring injuries (10.9 injuries per 1,000 team days) particularly in First Class (multi-day) cricket compared to other positions for that format. Batting and fielding had substantially higher incidence of hamstring injury in T20 cricket compared to bowling, with batsmen also more likely to sustain a hamstring injury during One-Day 50-over cricket (Orchard et al., 2017).

Forrest et al. (2017) conducted a systematic review into risk factors for non-contact injuries for fast bowlers, given the high injury risk associated with this position. From 1,265 articles that were screened, only sixteen studies (five cross-sectional, eleven cohort studies) met the inclusion criteria and were included in the qualitative synthesis. The authors identified several bowling biomechanics (excessive lateral trunk flexion and pelvis/hip kinematics) and various neuromuscular deficiencies (reduced trunk endurance, poor lumbo-pelvic-hip movement control and early signs of lumbar bone stress) as risk factors for non-contact injury. Conflicting results were found in studies examining mixed technique, bowing workload and quadratus lumborum asymmetry. Of the five cross-sectional studies, three were rated as high risk of bias and two as very high risk of bias. What's more of the eleven cohort studies, only three were rated as low risk of bias with the other eight as high risk of bias with The Newcastle-Ottawa Quality Assessment Scale. Reflective of Australia leading the way in published cricket research, 75% of the participants in the studies included in the systematic review were from Australia.

The only injury prospective cohort studies at elite level that has not found similar trends for fast bowler prevalence and incidence have been conducted at tournaments. One was during the 2011 ICC Cricket World Cup where five teams (Zimbabwe, Sri Lanka, South Africa, Bangladesh and Pakistan) participated in injury surveillance (Ranson et al., 2013). The authors reported lower fast-bowler injury prevalence rates than had been reported previously (Ranson et al., 2013). Fast bowlers had similar prevalence (5%) to slow bowlers and batters, but this could have been due to the short nature of the tournament surveillance period and potentially the match format played (One-Day 50 overs). Similarly, Das et al. (2014) conducted injury surveillance during The Asian Cricket Council Under-19 Elite Cup, another One-Day format tournament in 2013, and found the highest proportion of injuries occurred during fielding (45.8%), followed by batting (33.3%, 10.4 injuries per 10,000 balls) and bowling (8.3%, 2.6 injuries per 1,000 overs bowled), with prevalence rates not reported. However, it is important to highlight the small sample (n = 28) and surveillance period. It is also important to note the findings from these two tournaments should be considered independently as it is not suitable to directly compare them given the samples included different ages and competition levels. The ICC Cricket World Cup involved senior elite players and the ACC Elite Cup comprised of players under-19 at junior level.

In summary, fast bowlers have the highest injury risk compared to other positions at elite level, although this has not been shown to be true in the lower levels of the games (with an equal risk across all positions) and tournaments. However, more research is needed to validate the finding of increased injury risk for fast bowlers at elite level tournaments due to the lack of research in this area. Fast bowlers are at increased risk of lumbar spine injuries, which collectively is the body part with the highest prevalence rates in the sport. Across all positions, hamstring strains have the highest injury incidence, with an increased risk for fast bowlers but batsmen also susceptible, particularly during T20 and One-Day match formats.

2.5.9. Summary

There are several extrinsic and intrinsic factors that may influence a cricket player's injury risk. While the consensus statement provided guidelines with the aim of promoting consistent definitions and methodologies to enable comparison across studies, only a few studies have followed these guidelines and most of the research has been conducted in one setting (Australia). While patterns have emerged, there is need for a body of quality empirical evidence to test and validate the initial findings as well as further examining other potential risk factors that have yet to be investigated (e.g. physical characteristics). Many studies that have explored potential injury risk factors have used cross-sectional studies (Johnson et al., 2011) and have not yet investigated the interactions between different injury risk factors. What's more, there are a number of risk factors from the wider literature to also consider, that are outside the scope of this review.

Studying injury risk is complex and as the Multivariate Interaction Theory of Musculoskeletal Injury Precipitation (Kumar, 2001) suggested, every individual has several variables that can affect their injury risk and given the individual differences of such variables, there is an endless number of possible combinations that may result in injury. Injury surveillance is of utmost importance and needs to continue as well as implementation of more sophisticated statistical approaches (e.g. random forests) to the study of cricket injuries that could yield valuable insights and enhance understanding of risk factors specific to this unique sport.

2.6. Rationale for current work

The importance of injury surveillance has been highlighted in this review, with previous cricket injury epidemiology research focusing on attempting to identify common patterns across studies from different countries. While attempts have been made to standardise injury incidence and prevalence units, the ongoing challenge for injury surveillance research is the effectiveness of comparing incidence and prevalence between countries that have unique injury risk patterns to consider, resulting from varying amount of cricket and conditions in which it is played.

For injury surveillance in a particular context to yield meaningful insight, there needs to be enough longitudinal injury surveillance data from that setting to enable the identification of trends over time. This also serves to reduce any potential confounding variables that may arise when comparing general trends between countries and the different conditions associated with each unique environment. This has been possible with Australia where injury surveillance has been ongoing and reported from 1995 to 2016 (Orchard et al., 2006; Orchard et al., 2016a). However, the authors highlight that each country will still have their own biases that need to be considered for any analysis and comparison of injuries. For example, in Australia it has been suggested there is a preference for playing more fast bowlers and with larger grounds, batsmen and fieldsmen might run more during play (Orchard et al., 2016a), thus presenting a unique injury risk that needs to be considered when playing in this part of the world.

However, these are just hypotheses and require further study to test. While Australia play more cricket than a lot of the published countries at international level, more domestic cricket is played in England and Wales (Orchard et al., 2016a). However, there has been no injury surveillance research published from the country that represents a large proportion of elite cricket.

Injury epidemiology needs to be explored in elite cricket in England and Wales to contribute and bolster the data pool for more meaningful comparison of overall trends between previously published studies that also have injury surveillance data over a substantial period. What's more, previous cricket injury research has almost completely focused on the men's game and with a growing women's game, the risk factors associated with both formats need to be explored and rigorously tested, to enhance overall understanding as well as any potential differences between the men's and women's game that can inform future prevention strategies.

CHAPTER THREE

Injuries in England and Wales Elite Men's Domestic Cricket: A nine season review from 2010 to 2018

3.1 Introduction

An important aim for injury surveillance in any sport and indeed cricket, is to identify the injury types that pose the greatest threat to availability to inform and evaluate targeted injury prevention and management initiatives. Understanding the current injury situation is the first phase in O'Brien et al.'s (2019) three phase cycle for team-sport injury prevention. Once this has been established, injury risk factors and mechanisms are identified in the second phase, which can then inform preventative strategies introduced in the third and final phase. To effectively fulfil this aim, enough longitudinal data is ideally collected from the same setting (Ekegren et al., 2016), reducing any potential confounding variables that may arise when comparing general trends between settings and the different conditions associated with each unique environment. This has been possible in Australia, where injury surveillance has been ongoing since 1995 (Orchard et al., 2006; Frost & Chalmers, 2014; Orchard et al., 2016a). However, to date there is a lack of published research describing the magnitude and nature of injury risk in England and Wales domestic cricket, despite this setting representing a large proportion of elite cricket played worldwide.

In 2005, an international consensus statement was published outlining recommended methods for injury surveillance in cricket, with the aim of enabling comparison and improving the consistency and quality of research in the field (Orchard et al., 2005). The guidelines were initially used in several settings detecting a number of common injury trends, such as high incidence of hamstring strains, higher incidence in One-Day limited over cricket compared to other competition formats, a greater injury risk for fast bowlers over other player types/disciplines and high prevalence of lumbar spine injuries (Mansingh et al., 2005; Orchard et al., 2006; Frost & Chalmers, 2014; Orchard et al., 2016a). However, the injury incidence units (per 10,000 player hours) used in these studies were not suitable for comparing competition formats to a shorter format of the game (Twenty20 [T20] cricket), which emerged and became increasingly prominent after the consensus was published.

First-class matches are, typically scheduled for four days (approx. 24 hours of play per match in comparison to 2.5 and 7 hours for T20 and One-Day matches respectively), and even though there has been shown to be a higher number of injuries per first-class match, the hourly injury rate is lower than other competition formats (Orchard et al., 2010). To enable more appropriate comparison, it was proposed match injury incidence should be reported in days (per 1,000 player days) as opposed to hours (Orchard et al., 2010). This change was consolidated with its inclusion in the updated international consensus statement on injury surveillance in cricket, which also included a broader injury definition as well as definitions for; mode of, and activity at time of injury (Orchard et al., 2016b). However, to date only one study from Australia has employed the updated recommended injury surveillance units and included T20 cricket when assessing competition format as an injury risk in the men's game.[5] Notably, the authors acknowledged due to the lack of international T20 matches in some seasons, international and domestic level injury rates were combined for T20 cricket, limiting comparison with other competition formats where international and domestic injury rates are reported separately. Since higher injury incidence and prevalence have been found at international compared to domestic cricket (Mansingh et al., 2005; Orchard et al., 2006; Frost & Chalmers, 2014; Orchard et al., 2016a), different competitive levels should be analysed and reported independently to enhance the validity of the findings.

Accordingly, the primary aim of the present study is to compare match injury incidence between domestic competition formats in England and Wales, along with seasonal injury epidemiology and trends between 2010-18, to determine the priority injury problems and inform and evaluate associated injury management initiatives.

3.2 Methods

This prospective cohort study included all registered male players from the 18 First Class County Cricket (FCCC) clubs in England and Wales who have been involved in the England and Wales Cricket Board (ECB) injury surveillance programme (mean n = 507 players per season), encompassing the domestic competition season from April to September from 2010 through 2018 inclusive.

All injuries were recorded by FCCC club's medical staff, most often the lead physiotherapist on a purpose built central online medical records systems: Profiler (The Profiler Corporation, New Zealand, 2010-2016 inclusive), and Cricket Squad (The Sports Office, UK, 2017-2018 inclusive). To improve compliance, the ECB mandates consistent standards for injury and medical record-keeping for the domestic game through annual Cricket Science and Medicine Audit. Included in the medical record for each injury, the squad physiotherapists and/or Club Medical Officer records the injury location and diagnosis based on the Orchard Sports Injury Classification System Version 10 (Rae & Orchard, 2007), as well as cricket specific activities at the time of onset.

Before the ECB shared the injury surveillance data with the University research partner, the data was anonymised and checked for any errors by the ECB Injury Surveillance Officer who removed any identifiable data and assigned numerical IDs to players and injury records. Errors in the data included duplicate records and injures recorded that either remained open or needed updating or contained discrepancies, such as the body region recorded not matching the selected Orchard code). Such records were investigated by the ECB Injury Surveillance Officer (who is a trained physiotherapist with applied medical experience) and if needed, checked with the relevant practitioner or club who recorded the injury and updated accordingly. Any duplicate records were removed. All players provided informed written consent for their data to be routinely collected and analysed by ECB and a University research partner (Appendix A), arranged in conjunction with the players' union, The Professional Cricketers Association' (PCA). This was done at the time of annual registration and reviewed if there were any significant process or contractual changes at the start of pre-season. Ethics approval was obtained from the University of Bath, Research Ethics Approval Committee for Health (REACH).

The definition of 'injury' in the updated consensus on cricket injury surveillance is inclusive of illness[9] and in line with these guidelines, First-Class County practitioners defined and recorded any injury or illness that was considered to render the player unavailable for match selection, regardless of whether a match was scheduled on the day(s) the player was unavailable.

Injury incidence and prevalence was calculated following guidance in the updated consensus and to enable comparison to previous research, two injury incidence units are used, both applied retrospectively:

1. Match injury incidence includes all new and recurring (injury of the same type, on the same side, in the same body region, in the same season as an injury from which a player has previously recovered [Orchard et al., 2016b]) match injuries reported for all phases (batting, bowling and fielding). It considers only injuries occurring during major matches (Orchard et al., 2016b) and is provided for each competition format and then body region and activity at time of injury with the unit of injuries per 1,000 days of play (Orchard et al., 2016a).
2. Seasonal injury incidence is calculated from all new and recurring injuries per 100 players per season (183 days each domestic season) and allows for match and training injuries to be contained in one measurement. The consensus statement recommends the incidence unit of 'annual injuries per 100 players per year' (Orchard et al., 2016b), but given the fixed six-month nature of the domestic season in England and Wales, extrapolating the seasonal incidence to provide an annual incidence did not seem appropriate as it over-estimated the extent of the injury situation for the year. Particularly when there is distinct six-month off season for cricket in England and Wales with a greatly reduced number of injuries. Consistent with previous research[5] and the consensus statement (Orchard et al., 2016b), seasonal injury incidence is reported by body region and includes 'Medical illness' injuries.

Seasonal injury prevalence is presented as a percentage of players unavailable on any given day (i.e., not just match days, which would be 'match injury prevalence') by body region injured. With the ECB injury surveillance programme injuries are recorded as and when they occur as opposed to a daily status for each player. For this reason, the days lost recorded for each injury cover all seasonal days lost regardless of whether there was a match or not and it is not possible to align fixtures to the duration of the injury. Seasonal injury prevalence was calculated by the numerator of total missed seasonal days, with a denominator comprised of the total number of days in the surveillance period multiplied by the total number of registered players.

Injury incidence and prevalence were summarised with descriptive statistics (mean and 95% Poisson confidence intervals [CI]). Significant differences were assumed if the 95% CIs of individual categories did not overlap.

Statistical process control (SPC) analysis and charts were also used to detect trends in match injury incidence for each competition format over the nine seasons. The chart is comprised of upper and lower 'control limits', that are one, two and three SD above and below the overall mean injury incidence. SPC Shewhart u-charts of injury rates provide a quantitative monitoring tool to detect statistically significant changes over time (Schuh et al., 2017). With enough data, it allows for the identification of special variation from a particular data point's own historic baseline. The use of supplementary 'signalling' rules (the most of common of which were originally proposed in the Western Electric Handbook, [1956]) can highlight the need for further investigation when a supplementary rule has been met. These supplementary rules are:

- One or more points outside of the calculated control limits
- Two out of three consecutive points beyond two SD from the baseline
- Four out of five consecutive points beyond one SD from the baseline
- Nine consecutive points on one side of the historical baseline

3.3 Results

Total days played (mean = 1,463) across all FCCC decreased in the seasons towards the end of the surveillance period, with the total number of registered players (mean n = 505 players per season) relatively stable across the nine years (table 3.1).

Table 3.1: Total number of; registered players, days played for each competition format from 2010-2018

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Mean (95% CI)**
Number of registered players	512	503	494	502	502	505	509	506	512	505 (491, 520)
One-Day days played	215	218	205	217	148	146	154	148	144	177 (169, 186)
T20 days played	300	278	162	194	252	252	250	248	254	243 (233, 253)
First-Class days played	1064	1082	1084	1086	1096	1070	1092	934	870	1042 (1021, 1063)
Total days played	**1579**	**1578**	**1451**	**1497**	**1496**	**1468**	**1496**	**1330**	**1268**	**1463 (1438, 1488)**

The highest mean match injury incidence was found for Domestic One-Day cricket (mean: 254 injuries per 1,000 days of play, 95% CI 231-280), followed by T20 (mean: 136, 95% CI 121-152) and First-Class cricket (mean: 68, 95% CI 63-74). All competition formats were combined to provide overall match injury incidence for the activity at time of injury (table 3.2). Over the nine seasons, bowling consistently had the highest match injury incidence, followed by fielding and batting.

Table 3.2: Match injury incidence for activity at time of injury (new and recurrent injuries/1,000 days of play) for all formats combined from 2010-2018

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Mean (95% CI)**
Bowling	41.2	56.4	41.4	48.8	36.8	36.1	33.4	46.6	33.9	41.6 (38.1, 45.4)
Fielding	30.4	33.6	29.6	26.1	24.1	27.9	20.1	26.3	22.9	26.8 (24.0, 29.9)
Batting	22.2	26.6	15.2	21.4	22.7	24.5	18.7	31.6	17.4	22.3 (19.8, 25.1)
Non-cricket specific warm up	3.2	8.2	4.1	6.0	2.0	3.4	3.3	2.3	4.7	4.1 (3.1, 5.4)
Wicket Keeping	1.3	1.3	2.8	6.0	5.3	0.7	5.3	3.0	0.8	2.9 (2.1, 4.0)
All injuries	**98.2**	**126.1**	**93.1**	**108.3**	**91.0**	**92.6**	**80.9**	**109.8**	**79.7**	**97.7 (92.3, 103.4)**

Bowling presented the highest risk of injury across the competition formats except for T20 cricket (tables 3.3-3.5) where highest match injury incidence was for fielding (followed by bowling). The one-day competition format presented the highest risk to bowlers with the highest average mean match injury incidence (104.5 injuries per 1,000 days of play). Thigh injuries had the highest match injury incidence across all competition formats (table 3.6) except for First-Class cricket where hand injuries (table 3.7) had the highest match injury incidence (followed by thigh injuries). Thigh, hand, abdomen and lumbar spine injuries were regularly in the top four injured body regions across competition formats, except for the shortest T20 format, where shoulder and ankle replaced abdomen and lumbar spine injuries in the top four injured body regions (tables 3.8-3.9). For all injuries over the season, the thigh was the most common body region injured (highest average time loss incidence), followed by hand and lumbar spine injuries (table 3.10).

General seasonal injury prevalence rates were relatively consistent over the nine seasons (table 3.11). Lumber spine injuries resulted in the most days lost with 1.3% (mean) of players unavailable on any given day during the season from lumbar spine injuries. On average, 7.5% of players were unavailable on any given day during the domestic season when all injuries were considered (match and training).

Match injury incidence was plotted on SPC charts for each competition format: One-Day (fig 3.1); T20 (fig 3.2); First-Class County Championship (fig 3.3). None of the supplementary 'signalling' rules were fulfilled, with the charts illustrating the consistency in injury incidence for each competition format for each domestic season between 2010 and 2018, suggesting the relative injury risk for each competition format was stable during this period.

Table 3.3: Match injury incidence (per 1,000 days of play) for activity at time of injury for One-Day cricket from 2010-2018

	2010	2011	2012	2013	2014	2015	2016	2017	2018	Mean (95% CI)
Bowling	116.3	151.4	97.6	115.2	94.6	95.9	64.9	128.4	76.4	104.5 (90.0, 121.4)
Fielding	83.7	91.7	63.4	59.9	94.6	47.9	71.4	81.1	83.3	75.2 (62.9, 89.9)
Batting	51.2	50.5	29.3	46.1	60.8	41.1	84.4	74.3	41.7	53.3 (43.0, 66.1)
Non-cricket specific warm up	9.3	13.8	9.8	13.8	0.0	6.8	19.5	6.8	0.0	8.9 (5.4, 14.8)
Wicket Keeping	4.7	4.6	14.6	18.4	13.5	0.0	0.0	0.0	6.9	7.0 (4.0, 12.3)
All injuries	**265.1**	**311.9**	**214.6**	**253.5**	**263.5**	**191.8**	**240.3**	**290.5**	**208.3**	**248.8 (225.6, 274.4)**

Table 3.4: Match injury incidence rates (per 1,000 days of play) for activity at time of injury for T20 cricket from 2010-2018

	2010	2011	2012	2013	2014	2015	2016	2017	2018	Mean (95% CI)
Fielding	43.3	54.0	49.4	41.2	39.7	47.6	36.0	44.4	86.6	49.1 (40.7, 59.3)
Bowling	30.0	46.8	30.9	51.5	31.7	51.6	36.0	40.3	35.4	39.4 (31.9, 48.7)
Batting	26.7	43.2	24.7	46.4	43.7	43.7	20.0	56.5	27.6	36.9 (29.7, 45.9)
Non-cricket specific warm up	0.0	14.4	18.5	5.2	0.0	4.0	8.0	4.0	3.9	6.4 (3.7, 11.0)
Wicket Keeping	0.0	3.6	0.0	5.2	4.0	0.0	12.0	0.0	3.9	3.2 (1.5, 6.7)
All injuries	**100.0**	**161.9**	**123.5**	**149.5**	**119.0**	**146.8**	**112.0**	**145.2**	**157.5**	**135.0 (120.4, 151.3)**

Table 3.5: Match injury incidence (per 1,000 days of play) for activity at time of injury for First-Class cricket from 2010-2018

	2010	2011	2012	2013	2014	2015	2016	2017	2018	Mean (95% CI)
Bowling	29.1	39.7	32.3	35.0	30.1	24.3	28.4	35.3	29.9	31.6 (28.2, 35.4)
Fielding	16.0	16.6	20.3	16.6	10.9	20.6	9.2	12.8	18.4	15.7 (13.4, 18.5)
Batting	15.0	17.6	11.1	12.0	12.8	17.8	9.2	18.2	18.4	14.7 (12.4, 17.4)
Wicket Keeping	0.9	0.0	0.9	3.7	4.6	0.9	4.6	4.3	4.6	2.7 (1.8, 4.0)
Non-cricket specific warm up	2.8	5.5	0.9	4.6	2.7	2.8	0.0	1.1	1.1	2.4 (1.6, 3.6)
All injuries	**63.9**	**79.5**	**65.5**	**71.8**	**61.1**	**66.4**	**51.3**	**71.7**	**72.4**	**67.1 (62.0, 72.6)**

Table 3.6: Match injury incidence (new and recurrent time loss injuries per 1,000 days of play) for body region injured during all formats combined from 2010-2018

Body region	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Mean (95% CI)**
Thigh	16.5	33.6	19.3	16.7	11.4	10.9	10.0	21.8	19.7	17.8 (15.7, 20.2)
Hand	12.7	15.2	13.1	22.7	18.0	19.1	16.7	20.3	17.4	17.2 (15.1, 19.6)
Lumbar Spine	8.2	7.6	13.1	16.0	8.7	11.6	8.7	8.3	9.5	10.2 (8.6, 12.1)
Abdomen	8.9	7.0	6.9	10.0	7.4	10.2	12.0	9.0	8.7	8.9 (7.4, 10.7)
Ankle	8.9	12.7	7.6	7.3	8.7	5.4	4.7	9.8	6.3	7.9 (6.5, 9.6)
Shoulder	5.7	5.1	6.9	10.0	7.4	4.8	6.0	6.0	8.7	6.7 (5.4, 8.3)
Lower Leg	8.2	10.1	4.1	3.3	5.3	8.9	6.7	7.5	3.9	6.5 (5.3, 8.0)
Hip & Groin	5.7	12.0	6.9	4.7	2.7	4.8	6.0	6.8	8.7	6.5 (5.3, 8.0)
Knee	8.2	8.2	6.9	6.0	6.7	5.4	3.3	6.8	3.9	6.2 (5.0, 7.7)
Foot	8.2	5.1	1.4	2.0	3.3	2.0	2.0	2.3	4.7	3.5 (2.6, 4.7)
Head	0.6	2.5	1.4	0.0	2.7	6.1	3.3	4.5	7.9	3.2 (2.4, 4.3)
Chest	2.5	1.3	0.7	3.3	1.3	2.0	0.0	0.8	1.6	1.5 (1.0, 2.3)
Buttock & Pelvis	0.6	3.2	0.7	1.3	1.3	1.4	0.7	1.5	0.8	1.3 (0.8, 2.1)
Elbow	0.6	1.3	2.1	2.0	0.0	0.0	0.0	1.5	1.6	1.0 (0.6, 1.7)
Thoracic Spine	0.6	0.6	0.7	0.7	2.0	1.4	0.0	1.5	0.8	0.9 (0.5, 1.6)
Forearm	1.9	0.6	0.0	1.3	2.0	0.0	0.7	0.0	0.8	0.8 (0.4, 1.4)
Neck	0.6	0.6	1.4	0.7	1.3	0.7	0.0	0.0	0.0	0.6 (0.3, 1.2)
Wrist	0.0	1.3	0.7	0.0	0.0	0.7	0.0	1.5	1.6	0.6 (0.3, 1.2)
Upper Arm	0.0	0.0	0.0	0.0	0.7	0.0	0.0	1.5	0.0	0.2 (0.1, 0.6)
All injuries	**98.8**	**128.0**	**93.7**	**108.2**	**90.9**	**95.4**	**80.9**	**111.3**	**106.5**	**101.5 (96.2, 107.1)**

Table 3.7: Match injury incidence (new and recurrent time loss injuries per 1,000 days of play) for body region injured during First-Class cricket from 2010-2018

Body region	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Mean (95% CI)**
Hand	8.5	7.4	8.3	19.3	10.9	15.9	11.9	12.8	12.6	12.0 (10.0, 14.4)
Thigh	7.5	23.1	12.9	8.3	8.2	9.3	5.5	11.8	10.3	10.8 (8.9, 13.1)
Lumbar Spine	5.6	4.6	9.2	10.1	8.2	9.3	5.5	7.5	5.7	7.3 (5.8, 9.2)
Abdomen	7.5	1.8	5.5	5.5	3.6	5.6	8.2	3.2	6.9	5.3 (4.0, 7.0)
Lower Leg	7.5	8.3	2.8	2.8	4.6	5.6	3.7	4.3	4.6	4.9 (3.7, 6.5)
Ankle	5.6	4.6	7.4	6.4	5.5	1.9	3.7	6.4	2.3	4.9 (3.7, 6.5)
Shoulder	2.8	2.8	3.7	6.4	3.6	2.8	4.6	5.4	3.4	4.0 (2.9, 5.5)
Hip and Groin	1.9	6.5	4.6	1.8	0.9	3.7	5.5	5.4	4.6	3.9 (2.8, 5.4)
Knee	7.5	3.7	5.5	4.6	4.6	1.9	0.0	3.2	1.1	3.6 (2.6, 5.0)
Foot	5.6	5.5	0.9	0.9	3.6	0.9	0.9	3.2	4.6	2.9 (2.0, 4.2)
Head	0.0	2.8	0.9	0.0	2.7	4.7	1.8	3.2	9.2	2.8 (1.9, 4.1)
Chest	1.9	0.9	0.0	1.8	0.0	1.9	0.0	1.1	2.3	1.1 (0.6, 2.0)
Thoracic Spine	0.9	0.9	0.9	0.0	2.7	1.9	0.0	1.1	1.1	1.1 (0.6, 2.0)
Buttock and Pelvis	0.0	4.6	0.9	0.0	0.0	0.9	0.0	1.1	1.1	1.0 (0.5, 1.9)
Wrist	0.0	1.8	0.9	0.0	0.0	0.9	0.0	1.1	1.1	0.7 (0.3, 1.6)
Elbow	0.0	0.9	0.9	0.9	0.0	0.0	0.0	1.1	1.1	0.6 (0.2, 1.4)
Forearm	0.9	0.9	0.0	0.9	1.8	0.0	0.0	0.0	0.0	0.5 (0.2, 1.2)
Upper Arm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.2 (0.1, 0.8)
Neck	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.1 (0.0, 0.7)
All injuries	**63.9**	**81.3**	**65.5**	**70.9**	**61.1**	**67.3**	**51.3**	**73.9**	**72.4**	**67.5 (62.4, 73.0)**

Table 3.8: Match injury incidence (new and recurrent time loss injuries per 1,000 days of play) for body region injured during One-Day cricket from 2010-2018

Body region	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Mean (95% CI)**
Thigh	65.1	78.0	29.3	41.5	13.5	20.5	32.5	81.1	41.7	44.8 (35.7, 56.3)
Hand	27.9	50.5	34.1	41.5	67.6	41.1	32.5	40.5	27.8	40.4 (31.6, 51.6)
Abdomen	27.9	22.9	19.5	36.9	27.0	27.4	39.0	40.5	27.8	29.9 (22.5, 40.0)
Lumbar Spine	14.0	27.5	34.1	46.1	27.0	34.2	26.0	20.3	6.9	26.2 (19.4, 35.2)
Ankle	27.9	50.5	14.6	9.2	27.0	6.8	6.5	33.8	6.9	20.4 (14.6, 28.6)
Hip and Groin	18.6	27.5	24.4	13.8	6.8	13.7	6.5	27.0	34.7	19.2 (13.5, 27.3)
Knee	23.3	22.9	9.8	4.6	20.3	13.7	13.0	20.3	20.8	16.5 (11.2, 24.2)
Shoulder	14.0	9.2	19.5	23.0	20.3	6.8	19.5	6.8	20.8	15.5 (10.5, 22.9)
Lower Leg	9.3	18.3	9.8	4.6	13.5	20.5	32.5	6.8	6.9	13.6 (8.9, 20.9)
Foot	23.3	9.2	4.9	4.6	0.0	0.0	6.5	0.0	13.9	6.9 (3.9, 12.1)
Buttock and Pelvis	4.7	0.0	0.0	9.2	13.5	6.8	6.5	0.0	0.0	4.5 (2.1, 9.4)
Elbow	0.0	0.0	9.8	9.2	0.0	0.0	0.0	6.8	6.9	3.6 (1.6, 8.0)
Head	0.0	4.6	4.9	0.0	6.8	6.8	6.5	0.0	0.0	3.3 (1.4, 7.9)
Chest	4.7	0.0	0.0	9.2	6.8	6.8	0.0	0.0	0.0	3.1 (1.3, 7.4)
Forearm	9.3	0.0	0.0	0.0	6.8	0.0	6.5	0.0	0.0	2.5 (0.9, 6.7)
Neck	0.0	0.0	4.9	0.0	6.8	0.0	0.0	0.0	0.0	1.3 (0.3, 5.2)
Thoracic Spine	0.0	0.0	0.0	4.6	0.0	0.0	0.0	6.8	0.0	1.3 (0.3, 5.2)
Upper Arm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 (0.0, 0.0)
Wrist	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 (0.0, 0.0)
All injuries	**269.8**	**321.1**	**219.5**	**258.1**	**263.5**	**205.5**	**233.8**	**290.5**	**215.3**	**253.0 (229.6, 278.8)**

Table 3.9: Match injury incidence (new and recurrent time loss injuries per 1,000 days of play) for body region injured during T20 cricket from 2010-2018

Body region	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Mean (95% CI)**
Thigh	13.3	39.6	49.4	36.1	23.8	11.9	16.0	24.2	39.4	28.2 (21.8, 36.4)
Hand	16.7	18.0	18.5	20.6	19.8	19.8	28.0	36.3	27.6	22.8 (17.3, 30.1)
Shoulder	10.0	10.8	12.3	15.5	15.9	11.9	4.0	8.1	19.7	12.0 (8.2, 17.6)
Ankle	6.7	14.4	0.0	10.3	11.9	19.8	8.0	8.1	19.7	11.0 (7.4, 16.3)
Knee	0.0	14.4	12.3	15.5	7.9	15.9	12.0	12.1	3.9	10.4 (6.9, 15.8)
Lumbar Spine	13.3	3.6	12.3	15.5	0.0	7.9	12.0	4.0	23.6	10.3 (6.8, 15.6)
Abdomen	0.0	14.4	0.0	5.2	11.9	19.8	12.0	12.1	3.9	8.8 (5.7, 13.6)
Lower Leg	10.0	10.8	6.2	5.2	4.0	15.9	4.0	20.2	0.0	8.5 (5.4, 13.3)
Hip and Groin	10.0	21.6	0.0	10.3	7.9	4.0	8.0	0.0	7.9	7.7 (4.9, 12.2)
Head	3.3	0.0	0.0	0.0	0.0	11.9	8.0	12.1	7.9	4.8 (2.7, 8.7)
Foot	6.7	0.0	0.0	5.2	4.0	7.9	4.0	0.0	0.0	3.1 (1.5, 6.5)
Chest	3.3	3.6	6.2	5.2	4.0	0.0	0.0	0.0	0.0	2.5 (1.0, 6.0)
Neck	3.3	3.6	6.2	0.0	4.0	4.0	0.0	0.0	0.0	2.3 (1.0, 5.5)
Forearm	0.0	0.0	0.0	5.2	0.0	0.0	0.0	0.0	3.9	1.0 (0.3, 4.0)
Wrist	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	3.9	0.9 (0.2, 3.6)
Elbow	3.3	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8 (0.2, 3.2)
Buttock and Pelvis	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.4 (0.1, 2.8)
Upper Arm	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.4 (0.1, 2.8)
Thoracic Spine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0 (0.0, 0.0)
All injuries	**100.0**	**158.3**	**123.5**	**149.5**	**119.0**	**150.8**	**116.0**	**145.2**	**161.4**	**136.0 (121.4, 152.4)**

Table 3.10: Seasonal injury incidence (new and recurrent time loss injuries per 100 players per season) for body region from 2010-2018

Body region	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Mean (95% CI)**
Thigh	8.0	13.7	7.1	7.8	5.2	5.0	4.3	7.5	8.0	7.4 (6.6, 8.2)
Hand	6.4	6.6	5.5	8.6	8.4	7.9	7.7	6.3	7.4	7.2 (6.5, 8.0)
Lumbar Spine	6.6	6.2	6.1	7.6	6.4	5.9	6.7	6.7	4.9	6.3 (5.6, 7.1)
Ankle	5.7	6.0	4.0	4.0	4.2	2.8	4.3	5.1	5.5	4.6 (4.0, 5.3)
Abdomen	4.3	4.0	3.0	5.0	3.8	5.1	4.9	4.3	5.7	4.5 (3.9, 5.2)
Knee	4.5	4.8	3.8	3.8	3.0	2.6	2.4	3.4	2.3	3.4 (2.9, 4.0)
Lower Leg	3.9	5.0	2.4	2.6	3.2	3.2	3.3	3.2	2.7	3.3 (2.8, 3.9)
Shoulder	3.7	2.4	3.4	4.0	3.6	2.8	2.4	2.4	3.1	3.1 (2.6, 3.7)
Hip & Groin	3.3	5.0	3.2	3.4	2.2	2.8	2.2	2.4	2.9	3.0 (2.5, 3.5)
Medical Illness	2.7	2.6	3.0	4.2	1.6	1.6	3.3	2.8	5.3	3.0 (2.5, 3.5)
Foot	3.7	2.4	1.0	1.4	1.4	1.8	1.6	2.4	2.7	2.0 (1.6, 2.5)
Head	0.6	0.8	0.6	0.2	0.8	2.8	2.0	1.6	3.9	1.5 (1.2, 1.9)
Chest	1.4	0.8	1.0	2.2	0.8	1.0	0.4	0.6	0.6	1.0 (0.7, 1.3)
Elbow	1.4	0.4	1.0	1.0	0.8	0.0	0.2	0.8	1.0	0.7 (0.5, 1.0)
Buttock & Pelvis	0.2	1.2	0.4	1.0	0.6	0.4	0.6	0.8	1.4	0.7 (0.5, 1.0)
Thoracic Spine	0.6	1.0	0.4	0.8	0.8	0.6	0.2	0.6	0.6	0.6 (0.4, 0.9)
Neck	0.4	0.4	0.4	0.6	0.6	0.2	1.2	0.6	0.4	0.5 (0.3, 0.7)
Forearm	0.6	0.6	0.0	0.8	0.6	0.2	0.4	0.0	0.2	0.4 (0.2, 0.6)
Wrist	0.2	1.0	0.2	0.0	0.0	0.4	0.4	1.0	0.6	0.4 (0.3, 0.6)
Upper Arm	0.2	0.0	0.0	0.0	0.6	0.2	0.0	0.4	0.0	0.2 (0.1, 0.4)
All injuries	**58.4**	**64.6**	**46.8**	**58.8**	**48.4**	**47.1**	**48.3**	**52.7**	**59.2**	**53.8 (51.7, 56.0)**

Table 3.11: General seasonal injury prevalence from all time loss injuries by body region injured from 2010-2018

Body region	2010	2011	2012	2013	2014	2015	2016	2017	2018	Mean (95% CI)
Lumbar Spine	1.0%	1.2%	0.7%	1.3%	1.4%	1.6%	1.5%	1.6%	1.1%	1.3% (1.2, 1.5)
Hand	0.6%	0.7%	0.8%	1.1%	1.2%	1.1%	0.9%	0.7%	0.8%	0.9% (0.8, 1.0)
Ankle	0.7%	1.0%	0.7%	0.6%	1.0%	0.3%	1.0%	0.6%	0.9%	0.7% (0.6, 0.8)
Thigh	0.8%	1.3%	0.6%	0.6%	0.7%	0.4%	0.4%	0.6%	1.1%	0.7% (0.6, 0.8)
Abdomen	0.5%	0.6%	0.3%	0.8%	0.6%	0.8%	0.8%	0.5%	1.1%	0.7% (0.6, 0.8)
Knee	0.8%	0.6%	1.0%	0.7%	0.8%	0.5%	0.8%	0.2%	0.5%	0.6% (0.5, 0.7)
Lower Leg	0.8%	0.7%	0.4%	1.2%	0.7%	0.5%	0.6%	0.4%	0.3%	0.6% (0.5, 0.7)
Shoulder	0.7%	0.2%	0.7%	0.9%	0.7%	0.4%	0.5%	0.4%	0.3%	0.5% (0.4, 0.6)
Hip and Groin	0.4%	0.5%	0.6%	0.4%	0.4%	0.3%	0.5%	0.3%	0.2%	0.4% (0.3, 0.5)
Foot	0.8%	0.4%	0.2%	0.3%	0.2%	0.3%	0.2%	0.4%	0.6%	0.4% (0.3, 0.5)
Chest	0.1%	0.2%	0.1%	0.4%	0.1%	0.2%	0.1%	0.0%	0.1%	0.2% (0.1, 0.3)
Elbow	0.3%	0.0%	0.1%	0.2%	0.1%	0.0%	0.1%	0.2%	0.1%	0.1% (0.1, 0.1)
Head	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.1%	0.2%	0.2%	0.1% (0.1, 0.1)
Buttock and Pelvis	0.0%	0.1%	0.0%	0.2%	0.0%	0.1%	0.0%	0.1%	0.1%	0.1% (0.1, 0.1)
Wrist	0.0%	0.2%	0.0%	0.0%	0.0%	0.1%	0.2%	0.1%	0.1%	0.1% (0.1, 0.2)
Forearm	0.1%	0.1%	0.0%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1% (0.1, 0.2)
Thoracic Spine	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.1%	0.0% (0.0, 0.0)
Neck	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.1%	0.0%	0.0% (0.0, 0.0)
Upper Arm	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.1%	0.0%	0.0% (0.0, 0.0)
Medical Illness	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0% (0.0, 0.0)
All injuries	**7.6%**	**7.7%**	**6.3%**	**9.0%**	**8.2%**	**6.8%**	**7.9%**	**6.4%**	**7.8%**	**7.5% (7.2, 7.8)**

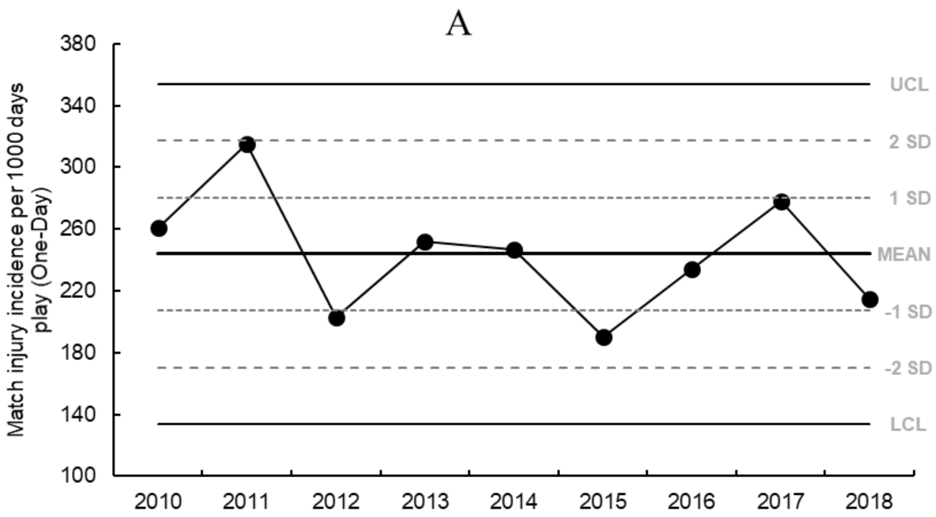

Figure 3.1: Control chart for match injury incidence (per 1,000 days play) for One-Day match format, for each season

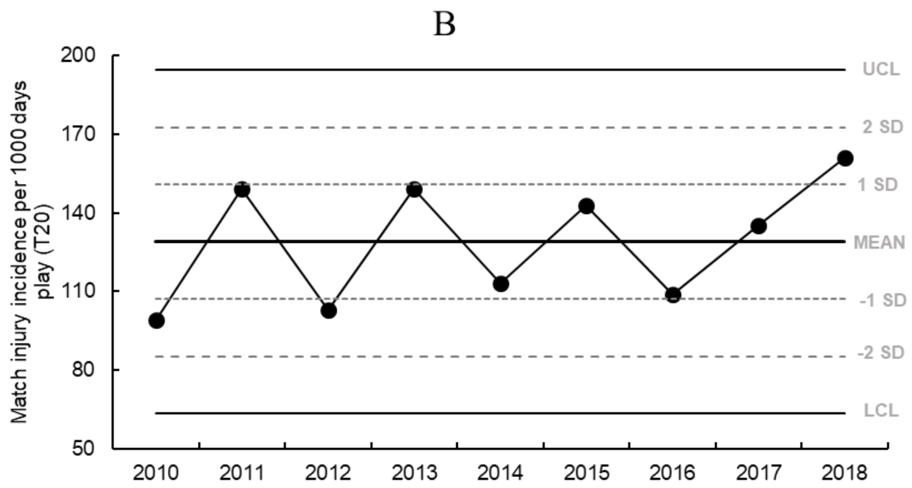

Figure 3.2: Control chart for match injury incidence (per 1,000 days play) for T20 match format, for each season

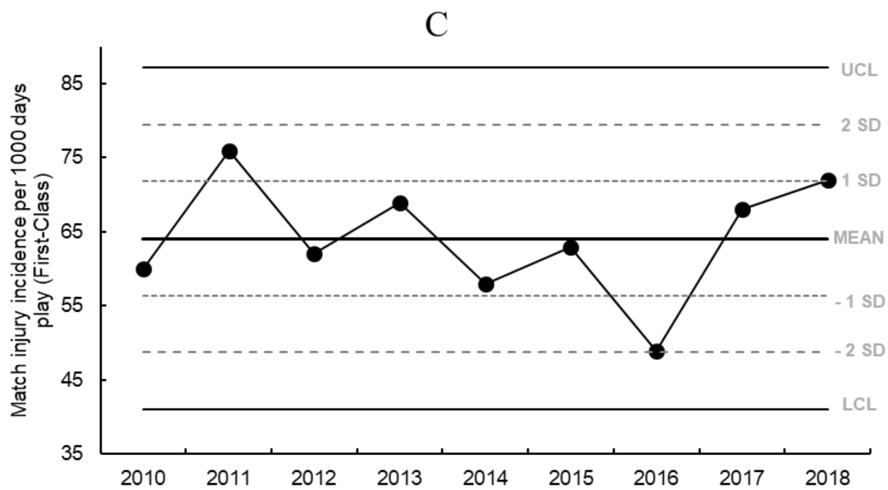

Figure 3.3: Control chart for match injury incidence (per 1,000 days of play) for First-Class match format, for each season

3.4 Discussion

This is the first study to explore the injury epidemiology of elite male cricketers in England and Wales and represents the largest body of work to date on the injury epidemiology of elite domestic cricket. For the first time, SPC charts were applied to sport injuries to detect trends in match injury incidence for each domestic competition format. The main aim of the study was to determine how match injury incidence differs between men's domestic competition formats in England and Wales to determine the priority injury problems in FCCC that can inform and evaluate injury management initiatives. One-day limited over cricket (which went from 40 to 50 overs in 2014) had the highest match injury incidence, with incidence for competition formats relatively consistent over the nine seasons.

While it is not always possible to directly compare, the general trend of higher match injury incidence in domestic One-Day cricket is consistent with the findings reported in Australia, the country that has played the most comparable quantity of domestic cricket with injury surveillance established over an equally substantial time (Orchard et al., 2006; Frost & Chalmers, 2014; Orchard et al., 2016a). None of the supplementary SPC 'signalling' rules were fulfilled indicating the lack of variation in the data. The 'control charts' provides injury trends in an understandable way for decision makers, with visual and quantitative representation of defined variations from baseline. Similar to their application in the Army (Schuh et al., 2017), SPC techniques could continue to be used in cricket to monitor and evaluate the effectiveness of any subsequent injury prevention strategies. However, consideration must also be given to the lack of true validation in using SPC charts in this context. There might be a thresholding effect with such techniques, and the optimal level for the limits suggested and used in this study, to fully detect meaningful changes in match injury incidence, were not investigated or determined.

Injury profiles were generally similar across competition formats and consistent with previous research, with thigh injuries found to have the highest time loss injury incidence (Orchard et al., 2006; Ranson et al., 2013; Frost & Chalmers, 2014; Orchard et al., 2016a). In Australian cricket, fast bowling was shown to be the activity most associated with hamstring injuries (Orchard et al., 2017), due to increased sprinting compared to other roles as measured by Global Positioning System [GPS] (Peterson et al., 2010). However, as more sprinting is required when fielding and batting in the shorter, more intense formats of One-Day and T20 cricket (Peterson et al., 2010; Peterson et al., 2011), a rise in hamstring injuries has also been found for these positions in these formats (Peterson et al., 2011). This notion has been further reinforced with the results from this study that found fielding to be the activity resulting in the highest injuries in T20, with bowling highest in the other formats. Hamstring injuries are common in positions and sports involving high speed running, accelerations and decelerations (Croisier et al., 2008; Williams et al., 2013; Ekstrand et al., 2011; Brooks et al., 2005; Orchard et al., 2013; Ahmad et al., 2014).

The high injury incidence of shoulder injuries (relative to other body regions) along with higher injury incidence when fielding than bowling in T20 cricket (relative to other activities) compared to other formats, is a unique finding to this paper. This was not found in the previous injury surveillance paper that included the T20 format (Orchard et al., 2016a), although it must be noted this paper combined both international and domestic cricket in their T20 injury rates due to low number of international T20 games. Although relatively high shoulder and fielding injury incidence was found in the injury profile of elite women's domestic T20 cricket (Warren et al., 2019), no previous research has focused on the injury profile of domestic men's elite T20 cricket and further research is needed to validate the potential unique injury risks this particular format may present.

The results of the current study further validate findings from previous research that has identified bowling as being the activity associated with the highest time loss injury incidence (Stretch, 2003; Mansingh et al., 2005; Orchard et al., 2006; Frost & Chalmers, 2014; Orchard et al., 2016a). This is most often associated with fast bowling and the ability to explore potential differences in injury rates between fast and spin bowlers is beyond the scope of this paper but warrants future investigation. The biomechanical demands of fast bowling create a unique injury risk in cricket, resulting in bowlers being particularly susceptible to lumbar spine injuries, in part due to the extreme trunk lateral flexion postures required for this activity (Bayne et al., 2016; King et al., 2016). Identification of this specific injury risk from the injury surveillance data has enabled the ECB to focus their research on practical management programmes aimed at understanding and reducing this particular injury burden (Bayne et al., 2016; Ranson et al., 2010).

Consistent with previous research, this study found lumbar spine injuries to have the highest prevalence (Mansingh et al., 2005; Orchard et al., 2006; Orchard et al., 2016a), which in Australia has been associated with high bowling workloads arising from the longer forms of the game (Orchard et al., 2016a). Although the match injury incidence for lumbar spine injuries was highest for One-Day cricket compared to the other competition formats, the absolute number of injuries was highest in First-Class Cricket due to the increased exposure in this format. However, it is important to also consider squad size and player demographics may fluctuate year on year and are not factored in with this current study. Age has been shown to be an important risk factor in fast bowler lumbar spine injuries (Johnson et al., 2012), but specific injury trends and causation are not debated in this paper.

There are limitations with the injury surveillance data contained within this study. Injuries are entered predominantly by the club's medical staff, most often the lead physiotherapist. As with any injury surveillance involving human data entry, there is risk of error not just in the data entered but the maintenance and updating of records. Over time, processes have been introduced to reduce such potential error and provide some assurance in the validity of the data. Standardised processes and definitions set by the ECB and the international consensus statement should help in reducing potential misclassification bias but with 18 different clubs in the County Championship, this remains a tangible risk.

This study formally establishes the extent of the current injury problem in elite male domestic cricket for both incidence and severity, as outlined in phase one of O'Brien et al.'s (2019) three phase cycle for team-sport injury prevention. Even though it seems injury incidence has remained stable over the nine seasons, this data has guided ECB research efforts into the second and third phase of identifying injury risk factors and introducing injury prevention strategies. Along with the aforementioned efforts to reduce the burden of lumbar spine injuries there have been practical changes to the game to enhance player safety. The identification of high injury incidence of helmet related facial injuries, which was only recognised from analysing data collated across all FCCC clubs, spurred the ECB to drive a change in international helmet safety standards (Ranson et al., 2013).

Future research should be guided by the continued need to identify injury risk factors and mechanisms that can inform injury prevention strategies, with the consistent injury rates highlighted in this study suggesting more work is needed to effectively reduce injury incidence across the domestic game. Based on these findings, which further validate previous research, priority should be given to thigh muscle and lumbar bone stress injuries, which have the highest incidence and prevalence respectively.

3.5 Conclusion

This study found One-Day cricket to have the highest time loss injury incidence rates, followed by T20 and First-Class County Championship in England and Wales. Overall, most injuries were sustained whilst bowling, with hamstring injuries being the most common, and lumbar spine having the highest prevalence. Injury incidence and prevalence were relatively consistent for all injuries across the nine seasons. These findings provide a robust empirical base for the extent of the injury problem in domestic cricket played in England and Wales, which can continue to guide future research in identifying injury risk factors and mechanisms that can inform injury prevention strategies.

CHAPTER FOUR

Negative association between injuries and team success in professional cricket: A 9-year prospective cohort analysis

4.1 Introduction

It has been proposed that athlete availability (through not being injured) is as significant a factor in team sport success as player skill (Orchard, 2009), with injuries shown to have a negative association with team and individual athletic achievement (Drew et al., 2017). Injury epidemiology studies often explore the extent of the injury problem through incidence/prevalence rates, but the extent to which injuries influence team success may be more practically relevant to coaches (Eirale et al., 2013). The link between injuries and performance also needs to be understood by stakeholders in sports clubs to ensure adequate resource allocation to injury prevention strategies (Hägglund et al., 2013).

A systematic review investigating the association between injuries and team success across different sports found evidence that increased availability of team members/athletes increased the likelihood of success (Drew et al., 2017). Though seven of the 14 included studies had low risk of bias, a challenge with synthesising and comparing studies in this subject area is the mix of statistical methodology, injury/success measures, and varying time periods of data collection. These challenges make it difficult to adequately generalise the findings and to date, no study has explored the relationship between injury and success within the context of cricket. In cricket, bowling has the highest risk of injury (Orchard et al., 2006; Frost & Chalmers, 2014; Orchard et al., 2016a) and yet if an injury occurs, currently a bowling substitute cannot replace this player, which might have a major effect in the context of a team with a limited number of specialists in this role. Furthermore, if high performing players are unavailable for selection because of injury, the strength of the team is compromised.

Several studies investigating the injury-success relationship have used injury incidence rates as an injury measure but examining injury frequency alone does not adequately account for the varying severity of time-loss injuries (Hägglund et al., 2013). Instead, a measure of injury burden ('overall match injury incidence rate x mean absence per match injury'), which incorporates both frequency and severity of injuries, may be more suitable for assessing the impact of injury on team success, as this measure is directly associated with athlete availability (Brooks & Fuller, 2006). One 24-team football study that explored the association between both injury incidence and injury burden (independently) and team performance over 11 seasons found more significant associations between injury burden and three performances measures (final league ranking, points per league match and a measure that reflects success in European cup competitions). Moderate negative associations between injury burden and success measures were also found in professional Rugby Union (Williams et al., 2016). This study utilised linear mixed modelling to examine both within- and between-team effects; a within-team reduction in injury burden of approximately 42 days per 1000 player hours was associated with the smallest worthwhile change in league points tally (±3 league points). Thus, there is growing evidence of a negative association between injury burden and team success (Drew et al., 2017). However, there are still only a small number of studies in this area and no studies have explored this relationship in elite cricket.

Providing evidence of an association between injury measures and team success may be useful when attempting to communicate the importance of injury prevention to elite cricket stakeholders, and when striving to implement injury prevention initiatives within this setting. As such, the aim of this study was to examine the association between injury measures and team success in professional cricket teams in England and Wales.

4.2 Methods

A prospective cohort design was used to record all match time loss injuries for all first XI players associated with all 18 First-Class County Cricket (FCCC) clubs (across Divisions 1 and 2) in England and Wales, for nine seasons from April to September from 2010 to 2018 inclusive. All teams were involved in the England and Wales Cricket Board (ECB) injury surveillance programme, which was co-ordinated by a central 'Injury Surveillance Officer' who provided advice and guidance (on matters such as compliance, injury definitions, data collection) to the lead physiotherapists at each club responsible for recording injuries.

All injuries were recorded on purpose built central online medical records system: Profiler (The Profiler Corporation, New Zealand (2010-2016 inclusive), Cricket Squad (The Sports Office, UK) (2017-2018 inclusive), supported by ECB's Injury Surveillance Officer. To help ensure compliance, injury recording was mandatory and enforced through ECB annual Science and Medicine audit on injury and medical records.

Each player registered to one of the 18 First-Class County Cricket (FCCC) clubs was informed of the injury surveillance programme and provided individual consent (Appendix A) for their data to be routinely collected and analysed by ECB and a University research partner (mean n = 507 players per season). This was done at the time of annual registration and reviewed if there were any significant process or contractual changes at the start of pre-season. The study was approved by University of Bath, Research Ethics Approval Committee for Health.

In line with cricket injury surveillance guidelines (Orchard et al., 2016b), First-Class County practitioners defined and recorded any injury or illness that were considered to render the player unavailable for match selection during the season, regardless of whether a match was scheduled.

The injury measures used in the current study were match injury incidence (number of match time-loss injuries per 1,000 days of play), and match injury burden ('overall match injury incidence rate x mean absence per match injury'), expressed for each team as number of injury days lost per 1000 days of play to account for both the frequency and severity (days lost from competition and practice) of injuries. The domestic competition structure in England and Wales sees 18 FCCC clubs compete in three competition formats during the domestic season (April to September inclusive). Two formats are tournament competitions with a group and knockout stage played in 'blocks' of single day fixtures (One-Day 50 over and T20 cricket). The County Championship is a league played throughout the season with each fixture scheduled for four days. Injuries from all competition formats were included in the analysis as an injury sustained in another format (e.g. One-Day cup) would still render the player unavailable for selection in a County Championship match. If a team played more days as a result of progressing in one of the two shorter format cup competitions, this was accounted for by use of actual days played for each format each season.

County Championship league points tally (16 points awarded for a win, eight points for each team in a tie and five points apiece if a match is drawn) was the team success measure used in this analysis. Out of the three domestic cricket competitions each season, the County Championship is the only format with fixtures that run the entire season and a league points tally. The other two competitions (One-Day 50 over and T20) are shorter cup competitions and thus performance in these competitions is difficult to quantify.

The analyses were based on the statistical methods developed to investigate the association between performance indicators and match outcomes in Rugby Sevens (Higham et al., 2014) and injury and success in Rugby Union (Williams et al., 2016). All estimations were made using the *lme4* package (Bates et al., 2020) with *R* (V.3.5.2, R Foundation for Statistical Computing, Vienna, Austria). Prior to completing the within-team analysis, both injury measures were standardised by converting to within-team Z-scores.

A linear mixed model determined the association between injury measures and performance *within* each team (across the multiple seasons). The fixed effects included were injury measures (match incidence rate or match injury burden, vis separate models) and the division a team was competing in during a given season, with team success (County Championship league points tally) the dependent variable and a random effect for team to account for repeated measurements. Team squad size (number of registered players for each squad each season) was included in the model to control for its possible effect. Effects were evaluated as the change in team performance associated with a two within-team SD increase in the injury measures, representing a change from a typically low (-1SD) to typically high (+1 SD) value (Hopkins et al., 2009).

Inferences regarding the effect of the injury variables were assessed using the smallest worthwhile difference in team success and magnitude-based inferences (Hopkins et al., 2009). The smallest worthwhile difference was given by 0.3 of the typical variation in the team success measures between seasons (Hopkins et al., 1999). This difference was calculated as the SD of the average season-to-season change in each team success measure, multiplied by 0.3 (Higham et al., 2014). Following this method, the threshold for smallest worthwhile change in County Championship points tally was calculated to be 13 points. In the County Championship, 16 points are awarded for a win and throughout the study period the average points differential between teams finishing 7th versus 8th in Division 1 (relegation to Division 2) was 11, providing support for its use as a practically meaningful points difference.

Between-team effects were analysed to determine how injury measures of teams that were on average more successful over the study period (higher average points tally) compared to those less successful, by averaging the injury and team success measures for each team across the nine seasons. Spearman and Pearson correlation coefficients were used (depending on significance of Shapiro Wilks test for normality) to assess between-team associations. A correlation of ± 0.3 (moderate) was adopted as the smallest worthwhile effect for between-team Pearson correlations (Hopkins, 2010).

A significance level of $p < 0.05$ was always used. In addition, magnitude-based inferences were used as a complementary analysis to evaluate and interpret the effects in terms of practical relevance (Impellizzeri et al., 2019). Effects were classified as *unclear* if the ± 90% confidence limits crossed thresholds for both positive and negative effects by >5%. Otherwise, the effect was clear and considered to have the magnitude of the largest observed likelihood value; positive if associated with superior team performance in a higher points tally, negative if associated with a poorer team performance, and trivial if associated with a non-substantial (below the smallest worthwhile change threshold) change in team performance. The effects were then qualified with a probabilistic term to provide more informative inferential assertions about the magnitude of the effect (Hopkins et al., 2009), using the following scale: <0.5%, *most unlikely*; 0.5-5%, *very unlikely*; 5-25%, *unlikely*; 25-75%, *possible*; 75-95%, *likely*; 95-99.5%, *very likely*; >99.5%, *most likely* (Batterham & Hopkins, 2006).

4.3 Results

In total, 14,163 team days of play, 1,343 match time-loss injuries and 40,863 seasonal days lost were recorded during the study period. This resulted in a match time-loss injury incidence rate of 94.8 injuries per 1,000 days of play (90% CI 83.3 to 107.9). The mean severity of all recorded match time-loss injuries was 25 ± 11 days, with a further breakdown of team means (in any given season) for success and injury measures provided in Table 4.1.

Table 4.1: Team means (90% CI) for any given season over the nine-year study period

Performance/Injury Measure	Mean (90% CI)
Days played	81 (71.2, 92.2)
Squad size	28 (24.6, 31.9)
County Championship points	175.0 (153.8, 199.1)
Match time-loss injuries	8.3 (7.3, 9.4)
Match injury severity	25.1 (22.1, 28.6)
Match injury burden (per 1,000 days of play)	2541.1 (2233.0, 2891.7)
Match injury incidence (per 1,000 days play)	102.2 (89.8, 116.3)

The within-team effect of a 2 SD increase in each injury measure (incidence and match burden) on performance (County Championship points tally) is shown in fig 4.1, along with the effect within each division. Additional interaction effects between squad size and injury measures were explored and removed from the model as they did not improve model fit and explained no additional variance in team success. Both injury measures showed *possibly negative* (probabilistic term) associations with team success (25-75% possible likelihood) in Division 1, but effects were *trivial* in Division 2. Based on the average within-team effect in Division 1, a reduction in match injury incidence of 2 match time-loss injuries per 1,000 days of play per club (90% CI 1.4 to 2.9, $p = 0.10$), or a reduction in match injury burden of 75 days per 1,000 days of play (90% CI 50.2 to 109.0, $p = 0.053$) in any given season was associated with the smallest worthwhile change in County Championship points (±13 points) as illustrated in fig 4.1.

As the Shapiro Wilks test for normality was significant for match injury incidence ($W = 0.79$, $p < 0.01$) but not significant for match burden ($W = 0.93$, $p = 0.12$), Spearman and Pearson correlation were used to assess between-team associations of injury measures on performance, respectively. The correlation between match injury burden and performance met the adopted moderate correlation (± 0.3) threshold for the smallest worthwhile effect for between-team correlations ($r = -0.36$; 90% CI -0.66 to 0.05; *likely negative,* $p = 0.15$) and is displayed in Figure 2. The Spearman correlation between team success and match injury incidence ($r = -0.25$; 90% CI -0.59 to 0.17, $p = 0.32$) was *unclear* (Fig 4.2).

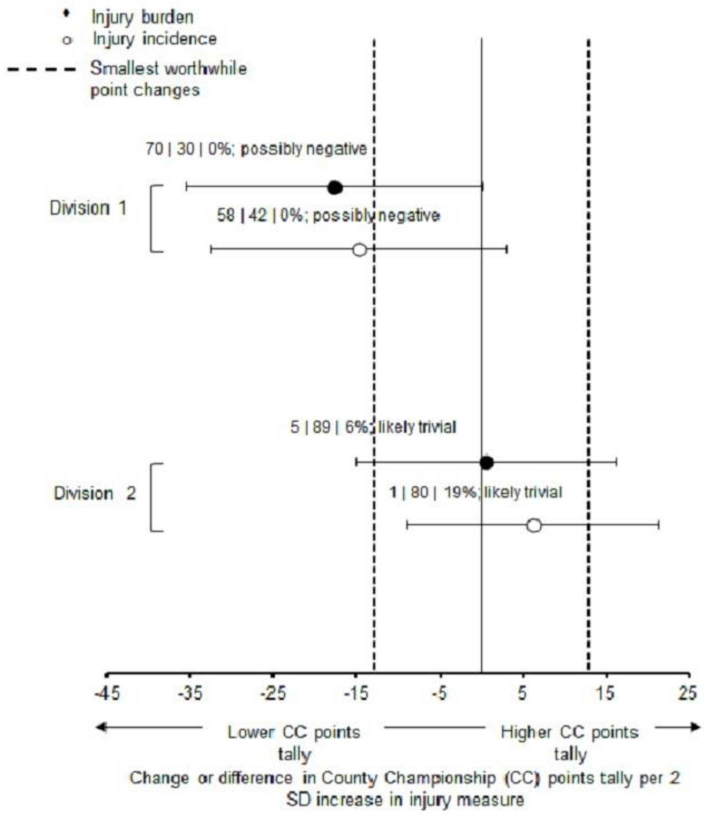

Figure 4.1: Plot for within-team changes of injury measures on Country Championship league points tally for each division.

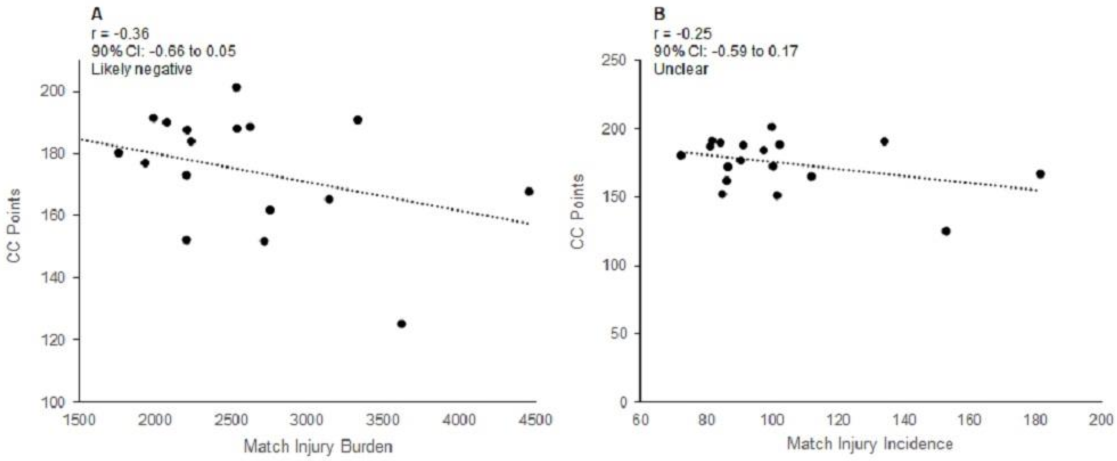

Figure 4.2: Pearson and Spearman correlation for (A) match injury burden and (B) match injury incidence and team success (County Championship league points tally).

4.4 Discussion

This study aimed to examine the association between injury measures (match injury incidence and burden) and team success in professional cricket teams in England and Wales. Both injury measures demonstrated *possibly negative* associations with County Championship points tally, with two SD decreases in injury burden associated with substantial (worthwhile) improvements within team success when teams were in Division 1, but not when they were in Division 2. Between-team differences in match injury burden were also moderately associated with the team success measure, with teams that had low injury burden values typically accumulating more County Championship points across both County Championship Divisions.

These results provide some support for the growing evidence of the negative association between injury and team success (Hägglund et al., 2013; Drew et al., 2017; Williams et al., 2016). Proposed mechanisms for this effect include reduced ability to select the best players, disruption to match and training preparations through player unavailability, as well as potential negative physical and psychological effects associated with injury that can still affect performance after a player has returned (Ivarsson et al., 2013; Soligard et al., 2016). When the strongest team is often selected to play and with athlete availability suggested to be as important a factor in team success as player skill (Orchard, 2009), any injury can weaken a squad in any team sport. Due to the dynamic and complex nature of both injuries and performance in sport, only moderate associations between injury and team success were expected in this study. However, these findings still provide further empirical support for the importance of injury prevention efforts and effective injury treatments as a worthwhile part in the overall aim of improving team success that should be understood by stakeholders in sports clubs involved with resource allocation to injury prevention and treatment.

An average within-team change in injury burden of approximately 75 days per 1000 days of play per team per season was associated with the smallest worthwhile change in County Championship points (±13 points) in Division 1. Although this negative association was only found when teams were in Division 1, perhaps reflecting the different competitive standard between the two divisions. Injuries sustained in Division 1 may be more detrimental to a team’s overall performance in relation to other teams in the division. As injury burden accounts for frequency and severity of injuries, there are several possible ways a team could achieve a reduction this area. For example, one way would be for a typical club to reduce their total time-loss match injuries by two injuries per season (in the context of a mean eight match time-loss injuries per team per season during the nine season study period), alongside a four-day reduction in severity of all injuries (in the context of a mean match injury severity of 25 days across the 18 clubs during the study period). However, suggesting exact recommendations for how a team would reduce injury burden can be difficult, as the aetiology and mechanisms of injury as well as individual risk factors need to be considered before any injury prevention strategy is recommended. Based on the evidence of the association between injuries and team success, future research to enhance understanding of such risk factors to inform the development of injury prevention strategies would be worthwhile.

The exact way injuries influence team performance remains unclear from this study, as the analysis explored an association between injury and team success and thus causality cannot be directly inferred. Indeed, it may be that successful teams incur fewer time-loss injuries as a result of being successful. Bowling is an important factor in a cricket team's success and has consistently been found to be the main cause of time-loss injuries (Orchard et al., 2006; Frost & Chalmers, 2014; Orchard et al., 2016a). Winning teams who have efficient bowlers may take wickets quicker, resulting in bowlers with less exposure than a team who must bowl and field for longer periods. In addition, it may be that successful teams have greater budgets available for medical, rehabilitation and strength and conditioning staff (Williams et al., 2016). A larger overall squad size is considered to be favourable as it can accommodate any time-loss injuries better than a smaller squad. However, the interaction effects between squad size and injury measures were removed from this study as they did not improve model fit or explain any additional variance in team success, as was the case with a similar analysis in rugby union (Williams et al., 2016).

There are limitations with the findings of this study. The use of magnitude-based inferences as a complementary analysis to null hypothesis significance testing, allows the outcome to be interpreted in an understandable and practical way, as opposed to a model simply not being significant. However, a criticism of such techniques is that it does not adequately control Type I error (Sainani, 2018) and researchers can draw 'overly optimistic' conclusions from their data (Lohse et al., 2020). In relation to the analysis conducted in this study, there is no denying the high proportion of non-significant results. Overall, the association between injury and team success in this context was not strong, with just a moderate association found for injury burden in Division 1. Both injuries and team performance are two factors that in themselves have dynamic and multiplex natures, let alone the numerous non-linear interactions between them. It is difficult when conducting an analysis on this type of data to fully capture the complex and non-linear interactions amongst the multiple factors.

One such factor that provides another methodological consideration, is the lack of adjustment for the relative importance of an injured player within the team. An injury to a highly valued player is likely to have a greater impact on team success. A study in Australian Football League (AFL) has attempted to adjust for this using player weighting based on both a club-based rating system (obtained from the AFL) and league-wide 'Brownlow Medal votes' (sourced from publicly available data), which is a '3-2-1' voting system used by field umpires at the conclusion of an AFL match, with three votes awarded to the best player of either team (Hoffman et al., 2019). This study found that when the 'value' of injured players was accounted for, injury was more strongly associated with team performance than when it was not, with weighted injury burden explaining up to 12% of the variation in final table position.[20] Finalists were more likely to have a higher player match availability than teams that were non-finalists. Future research on the association between injury and team success should consider including a weighting for players based on their importance within a team. This is especially pertinent to cricket, which (to a greater extent than most team sports) is effectively an individual sport within a team context, with much of the game focused on one bowler against one batsman. With this mind, losing specialist players to injury is likely to have a bigger effect in cricket than in other sports.

Future research in this area should also consider including non-time loss as well as time loss injuries in their analysis. Only including those injuries that resulted in time loss may bias the findings and is a limitation of the current study. A player with a non-time loss injury will be available for selection, with (or without) modified activity that can compromise their ability to perform at their usual standard, which could influence team success.

4.5 Conclusion

This study found negative associations between injury burden and team success, with the implication being that moderate reductions in injury burden could have a worthwhile effect on the performance of a domestic cricket team in the County Championship Division 1, but not Division 2. Such findings highlight the link between injuries and team success that need to be understood by stakeholders in cricket and emphasises the importance of injury prevention efforts.

CHAPTER FIVE

"You come up with different theories every year": Practitioner perceptions of injury risk factors and player monitoring practices in elite men's domestic cricket.

5.1 Introduction

Workload quantifies the demands imposed on an athlete during matches and/or training (Gabbett et al., 2014), and has been shown to be associated with injury risk across many sports including cricket (Dennis et al., 2005; Orchard et al., 2009; Orchard et al., 2015; Tysoe et al., 2020). Cricket has differing game formats, with First-Class matches typically scheduled for four days (approx. 24 hours of play per match) and T20 and One-Day matches scheduled for one day (typically 2.5 and 7 hours, respectively), as well as unpredictable match durations, resulting in substantial variations in player workload (Orchard et al., 2010), making monitoring player workloads practically challenging (Christie et al., 2020).

The aim of appropriate workload management is to lead to positive physical adaptations that may minimise the influence of fatigue and reduce injury risk (Hulin et al., 2014; Drew et al., 2016). Player monitoring (as part of this process) needs to be individualised, with clear variation in workload responses between fast bowlers demonstrated in a sample of adolescent male cricketers on an international development programme (Warren et al., 2018).

Given the importance of player monitoring to help reduce injury risk, there is a noted lack of literature on player monitoring in team sports like cricket (Christie et al., 2020). Understanding the perceptions of sports practitioners, such as physiotherapists and strength & conditioning coaches, to injury and player monitoring practices could help guide practice within the team sports environment. In European elite football practitioners have been found to place importance on external workload variables as injury risk factors, with poor player adherence identified as a barrier to effective player monitoring and subsequent injury prevention initiatives (McCall et al., 2016). In professional rugby union, conditioning staff deemed previous injury, Global Positioning System (GPS) metrics, collision counts, and age to be the most important risk factors for managing future injury risk (West et al., 2019).

At present, there has been no systematic reporting of current practitioner perceptions of injury risk factors and player monitoring practices at First Class County Cricket (FCCC) clubs participating in England and Wales Cricket Board's (ECB) national competitions, and consequently what barriers and facilitators there may be to future prevention strategies in this area. Therefore, the aim of the current study was to capture and better understand the current perceptions of injury risk factors and player monitoring practices in elite men's domestic senior cricket.

5.2 Methods

5.2.1 Study design

This was a pragmatic, cross-sectional mixed-methods study, following a concurrent triangulation strategy where both quantitative and qualitative data was collected to permit comparison between the results from each element (Creswell, 2003). The complementary strengths of both quantitative and qualitative methods can provide greater insights when both results are collectively considered. A quantitative survey identified injury risk perceptions and prevention initiatives and qualitative interviews explored in more detail the current practice and perceptions of player monitoring in elite level domestic cricket in England and Wales. The Consolidated Criteria for Reporting Qualitative Research (Tong et al., 2007) was used to demonstrate credibility of the qualitative methods (Appendix 1). This study was approved by institutional Research Ethics Approval Committee for Health (REACH) [reference: EP 17/18 257].

5.2.2 Data collection and participants

Survey: Injury prevention strategies

A survey was adapted from McCall et al's (2016) UEFA Elite Club injury prevention strategies survey and was sent via email to sport practitioners (over the age of 18) at the 18 ECB First-Class County Cricket (FCCC) Clubs. The original survey was developed for use with UEFA and designed by sports science and medicine practitioners with knowledge and experience in professional elite football and peer-reviewed survey-based research and developed from previous research (McCall et al., 2014; McCall et al., 2015). McCall et al pilot-tested the original survey five football clubs participating in the UEFA Elite Club Injury Study research initiative (McCall et al., 2016). These were clubs selected by UEFA as being qualified among the 32 teams in the UEFA Champions League ground-play stage (for the 2014-2015 season) or participated in the play-off stage or were ranked as 1 of the 50 best teams in Europe during the period of 2001-2014. The survey includes four sections: 1) perceived risk factors for injuries, 2) screening tests and monitoring tools used to identify injury risk, 3) injury prevention strategies utilised, perceived effectiveness and implementation strategies, 4) player and coach adherence related to performing an injury prevention programme and commitment to complying with individualised player recommendations (McCall et al., 2016). The survey was adapted for use in this study by including cricket-relevant examples in the responses as well as excluding the final two sections focused on injury prevention strategies and adherence, as these were not relevant to the aims of the current study (Appendix C). Participants were required to provide explicit consent before completing the survey. Responses were received from 9 first-team physiotherapists (39%) and 14 strength & conditioning coaches (61%), with representation from each club. All responses were confidential and anonymised after data collection for analysis and reporting, with a unique numerical code assigned to each response for identification purposes.

Interviews: Perceptions and practices of player monitoring in elite cricket

A sub-group of physiotherapists and strength & conditioning staff (*n* = 10, with 0 refusing to participate or dropping out) from six FCCC clubs were purposively sampled for follow-up interviews about their current practices and perceptions of player monitoring. To promote equitable opportunity to take part in the research, all sports practitioners were provided with the opportunity to express interest to participate in the interviews at the end of the online survey. The eligibility criteria for participation were: (1) a member of the medical or strength & conditioning department at an FCCC club; (2) involved with player management. For those who participated in the interviews, the average time served within their role at the club was 1.8 years (± 1.9) for physiotherapists and 2.9 years (± 1.5) for strength & conditioning staff. Two physiotherapists who participated in the interviews had served less than 1 year at the club (even though they had considerable professional experience outside of cricket) and were joined in the interview by a strength & conditioning coach with greater time served at the club (mean = 3.7 years ± 1.5). Four FCCC clubs had both a physiotherapist and strength & conditioning coach attend the interview (e.g. two-on-one), whereas for two clubs, due to changes to the team's schedule and practitioner availability, one physiotherapist (1.5 years time served at the club) and one strength & conditioning coach (2.6 years time served at the club) was present with the interviewer (e.g. one-on-one). The interviews were conducted by a single male interviewer (LG) who had previous experience conducting interviews. The interviewer had no experience as a sports practitioner and some exposure to cricket, as they were embedded with the National Governing Body (ECB) as a PhD candidate for approximately 18 months before the study. Some of the physiotherapists (*n* = 3) and strength & conditioning coaches (*n* = 2) participating in the study were aware of the interviewer's role, while others (*n* = 5) had no established relationship. A semi-structured interview guide was developed by one researcher (LG) and checked by two other researchers, to steer the interview dialogue, whilst allowing participants to say as much as they wished (McKay et al., 2020). The guide consisted of open questions on broad themes that were informed by the player monitoring questions from the survey, to draw out more information focused on potential monitoring tools used and the communication of data (Appendix D).

Interviews took place at either the home or away (where a club travelled for a fixture) FCCC ground during the domestic cricket season between May and September 2019. The interviews lasted 20-30 minutes and were audio recorded and transcribed verbatim. The transcripts were imported into NVivo qualitative data analysis software (QSR International Pty Ltd. V.10, 2012) as separate document sources for analysis. No additional field notes were made during or after the interviews and no repeat interviews were carried out. All responses were confidential and anonymised after data collection for analysis and reporting, with a unique numerical code assigned to each response for identification purposes.

5.2.3 Data Analysis

Survey

Raw data were exported from an online survey tool (JISC Online Survey, UK) into Microsoft 'Excel' software for analysis by the research team. The overall importance of risk factors was calculated by points awarded based on a Likert scale of perceived levels of importance (McCall et al., 2014; McCall et al., 2015; McCall et al., 2016). Consistent with previous research that developed the survey, a risk factor rated by participants as 'very important' was awarded 3 points, 'important': 2 points, 'somewhat important': 1 point, 'not sure': 0.5 and 'not important': 0 (McCall et al., 2016). Responses from each participant were then aggregated to rank risk factors from highest to lowest. A similar method was used to determine the most frequently endorsed reasons for 'importance' and 'factors impacting effectiveness' of player and workload monitoring. To rank tools used to identify and assess injury risk, points were awarded based on participants' selection of a response (out of a possible three) related to frequency of use. A tool that was used for 'continuous assessment throughout pre and in-season' was awarded 2 points, 'during pre-season only': 1 point and 'did not implement': 0 points. Similarly, points were then summed and ranked from highest to lowest. For the open-ended question of the perceived top three most important monitoring tools, word clouds were generated online (TagCrowd, USA, 2019) based on responses for each rating, with larger and darker words signalling greater frequency of mentions. Word clouds are a visual qualitative method that allows the reader to understand main themes quickly (McNaught et al., 2010), with their use encouraged in sport and exercise research (Phoenix, 2010).

Interviews

Thematic analysis was followed for the interview responses as it allows a more organic and flexible coding process and is more suited to research questions related to peoples' experiences, views and perceptions (Braun & Clarke, 2019). This process involves inductive coding without predefined categories or preconceived hypothesis and was conducted by one researcher. Development of themes was derived from the data and were created from the clustering of similar codes that could evolve throughout the coding process, with shared meaning captured around a concept related to the study aim (Braun & Clarke, 2014). The defined themes were then checked and validated by two other researchers.

The six phases of thematic analysis (Braun & Clarke, 2006) were followed in the present study: 1) the lead author familiarised themselves with the data, 2) initial codes were generated, 3) codes were collated into potential themes, 4) the themes were reviewed in relation to the coded extracts and entire data set, 5) the themes were defined and named, and 6) the report was produced. During the first two phases, all six transcripts were read and re-read to identify as many themes as possible. To ensure credibility, each transcript was compared and validated against the emerging categories to ensure no relevant data was inadvertently or systematically excluded or irrelevant data included (Johnson, 2011). These categories were then condensed in the third stage to produce themes. In the fourth phase, themes were reviewed and relevance to the research aims was confirmed for all. During the fifth phase, after discussion with co-authors who checked the themes, the theme ‘club support’ and ‘culture’ were combined into one theme with the subthemes ‘negative’ and ‘positive’.

Preliminary findings were then sent to participants to check interpretation accuracy, provide feedback, and request any part of their transcript to be removed. Any misinterpretation would have been clarified and one participant requested to withdraw a section of their transcript, which was removed from the analysis. This allowed for the findings to be checked, enhancing the validity of the interpreted data (Thomas, 2017). Interview findings for each club were also triangulated with their survey responses to check for consistency in responses across both methods (Creswell, 2003). This data harmonisation allowed the authors to note areas of convergence within the findings to strengthen the knowledge claims of the study (McKay et al., 2020). Any inconsistencies within the findings (of which there were none) would have been followed up and checked with the participant.

5.3 Results

5.3.1 Survey: Injury prevention strategies

Background information

Altogether, at least one sports practitioner from each of the 18 FCCC clubs submitted a survey response. Twenty-three survey responses were included in the analysis.

Perceived injury risk factors

The intrinsic risk factors frequently endorsed as being important were previous injury, followed by physical fitness and sleep (table 5.1). Reduced recovery time, congested match schedule, number of matches/minutes played, playing position, and training were the extrinsic risk factors most frequently endorsed.

Table 5.1: Top 5 intrinsic and extrinsic risk factors frequently endorsed by ECB FCCC club practitioners

Rank	Intrinsic risk factor	Accumulated points of importance	Extrinsic risk factor	Accumulated points of importance
1st	Previous injury	61	Reduced recovery time	62
2nd	Physical fitness	56	Congested match schedule	61
3rd	Sleep	52	Number of matches/minutes	52
4th	Accumulated fatigue	51	Playing position	52
5th	Psychological factors	47	Training load	52

Maximum points of importance = 69

Identifying and assessing injury risk

When identifying injury risk in players (most often used during pre-season) the most common tools used were evaluation of side-to-side muscle imbalance, flexibility assessment, and maximal physical fitness tests (table 5.2). Overs bowled in match and training, along with the acute:chronic workload ratio (ACWR), were the most frequently used tools by practitioners when continually assessing injury risk (table 5.2).

Table 5.2: Top 5 tools frequently endorsed by ECB FCCC club practitioners to identify and assess injury risk in players

Rank	Identify	Accumulated	Assess	Accumulated
1st	Evaluation of side to side	29	Overs bowled in match	45
2nd	Flexibility	29	Overs bowled in training	42
3rd	Maximal physical fitness test	27	ACWR	37
4th	Joint mobility/function	27	Rating of Perceived Exertion (RPE)	30
5th	Psychological evaluation	27	Number of matches/minutes	27

Maximum points of importance = 46

Monitoring tools

The top three most important monitoring tools as rated by county practitioners are summarised in word clouds. The larger and darker the word, the more frequently it was mentioned. Bowling workload monitoring was the most important monitoring tools used in county cricket, with player conversations also acknowledged (fig 5.1). Mentions of player ratings of perceived exertion (RPE) and ACWR became more prominent in the 2nd most important monitoring tools, with wellness starting to feature. Much more variation was found in responses for the 3rd most important monitoring tools, with wellness becoming more prominent along with physical screening and movement (fig 5.1).

Figure 5.1: Frequency of word mention for 1st, 2nd and 3rd most important rated monitoring tools

Reasons for player monitoring and factors impacting its effectiveness

Reducing injury risk was the most frequently endorsed reason for player and workload monitoring from FCCC club practitioners (fig 5.2). Player adherence followed by human resource and practical application of player and workload monitoring were the frequently endorsed factors perceived to impact the effectiveness of any monitoring efforts (fig 5.3).

Practitioner desires

Seventy four percent of respondents indicated there was more they would like to do to monitor players. GPS was the most frequently mentioned, with wellness and fatigue featuring as desirable measures practitioners would like to capture as part of their player monitoring.

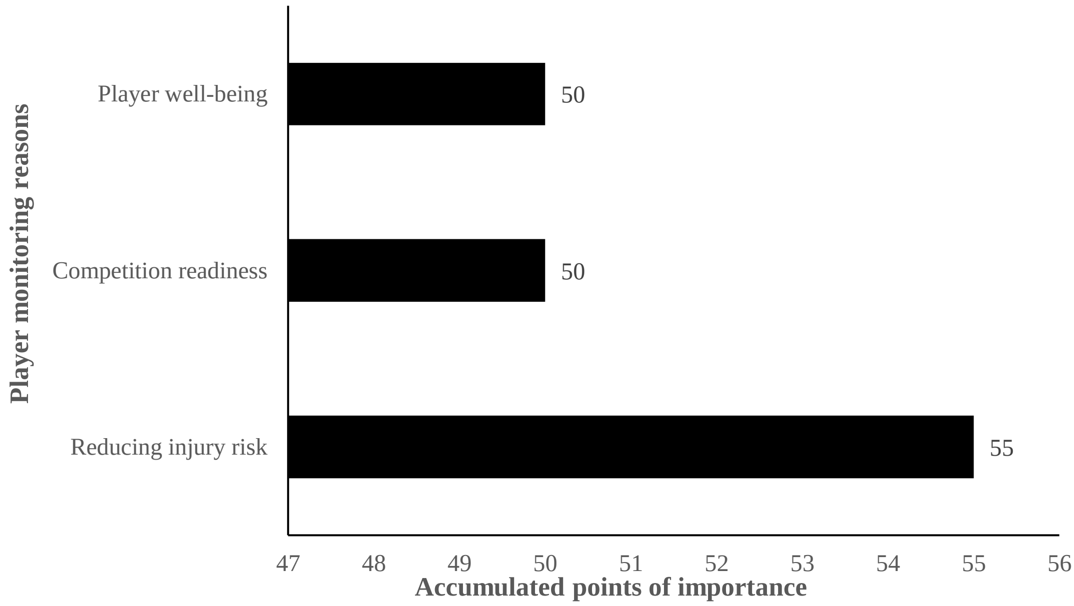

Figure 5.2: Top 3 frequently endorsed reasons for player and workload monitoring (maximum accumulated points of importance = 69)

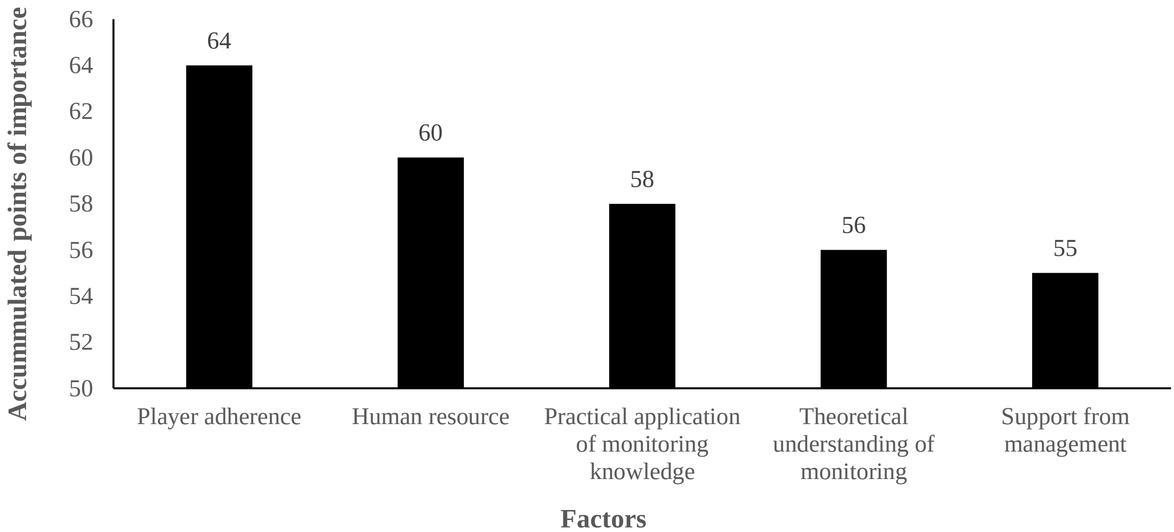

Figure 5.3: Top 5 frequently endorsed factors that impact effective workload and player monitoring (maximum accumulated points of importance = 69)

5.3.2 Interviews: Perceptions and practices of workload and player monitoring in elite cricket

Six core themes consistently emerged from the interviews: 1) Perceived importance of player monitoring, 2) Player adherence, 3) Player monitoring challenges, 4) Use of GPS 5) Pre-season preparations and 6) Club culture.

Perceived importance of player monitoring

All sport practitioners involved in the interviews recognised the importance of player monitoring. They believed that monitoring provides greater insight and understanding into the demands of the game and can better inform practice to adequately prepare and rehabilitate players. It was acknowledged that due to the complex nature of injuries, although player monitoring was useful it is only one part of a bigger picture. Furthermore, even though the importance of player monitoring was understood by practitioners, players and coaches may not always appreciate its importance.

Player adherence

Generally, player adherence levels (in relation to participation in player monitoring initiatives) were deemed to be acceptable by practitioners in this setting, with most players regularly completing any required self-report measures. Some of the participants acknowledged challenges in getting some players to 'buy-in': *'It's such a mix, I mean you've got some really professional ones and some, they couldn't care less' (P06).*

Sub theme: Strategies to improve adherence

Suggested strategies to improve player adherence to any monitoring efforts included practical steps such as notification reminders, but most focused on placing the needs of the player central to any communication around monitoring. Many participants acknowledged their role as practitioners in educating players about the value of any monitoring efforts. This included information about relevant benefits as well as emphasis on positive motivations for monitoring: how it can help the player with matters like injury prevention and overall promotion of playing and performing in cricket. Through this, any potential player concerns around monitoring are also mitigated: *'We educate them definitely; we just want to know how they are … To help them to help the team; everything is geared towards us being the best cricket team we can be' (S&CC02).* Several practitioners suggested greater player understanding as to why they are doing anything related to monitoring helps with improving adherence: '*we've done enough to try and explain to them that we're just trying to keep them on the park*' *(S&CC04)*.

Player monitoring challenges

Aside from player adherence, more general challenges around player monitoring were raised during the interviews. The nature of cricket as a sport presents a distinct challenge for practitioners and was alluded to by numerous participants. During the season, in a typical week a greater proportion of time is spent in competitive matches as opposed to training and it can be difficult to continually ensure players are physically prepared due to reduced recovery time between matches: '*in football you know, your whole* *preparation is led up to 1 game in a in a 7 day block potentially 2 in 7, we're playing 5 sometimes 5 or 6 of 7 [days], and actually so that that 1 day off or that those 2 days off, you know there's no chance we're going to be going, right actually we need you in to do this this' (P02)*. The additional challenge of managing the varying and unpredictable demands of the differing formats of the game, and ensuring players are suitably prepared for these was also mentioned: '*[when] there's been a change of format we seem to get more issues, so it's about bridging that gap between workloads' (S&CC02).*

Sub theme: Resource

Quite a few participants acknowledged that not only can Science & Medicine departments within clubs be quite small and generally busy through the season, budget and facilities can be challenges that impacts the effectiveness of monitoring efforts. Time demands because of limited resource can diminish the value of the insight generated from the monitoring data, with most analysis being retrospective in nature. However, it was suggested by one participant that such limited resource can actually be a positive, by allowing practitioners to keep things simple and consistent: '*we're quite limited with what we've got resource wise but I actually quite like that because it keeps it simple and consistent' (S&CC02).*

Use of GPS

The use of GPS emerged consistently through the analysis with its ability to track running loads its greatest application. This allowed practitioners to gain greater understanding of the different loads required for each format to more accurately inform not just pre-season preparations and returning from injury programmes, but throughout the season to ensure players are continually prepared physically to meet the (often varying) demands of the sport: *'there's a lot of GPS, we know roughly what a bowler covers in a day, roughly how much high speed running they cover for each format, it's all individual, but we know we've got an idea of that and to be fair that data helps us pre-season' (S&CC03).*

Sub theme: GPS challenges

Challenges with GPS were raised by most participants during the interviews. It emerged that some bowlers can find the equipment to be quite intrusive and some raised concerns that it could interfere with their bowling technique and negatively impact upon their performance: *'some are happy and others are like, 'no I'm not wearing them', erm 'cos it interferes with their bowling' (S&CC02)*. The cost of GPS was mentioned as an issue, as well as the challenge (and time) of collecting and analysing the data. It was also suggested the data provided by GPS was useful to a point: *'It's getting to the point now where erm a lot of the information is same coming back' (S&CC01)*. Once again, the distinct nature of cricket arose as an issue for those wearing GPS in comparison to other sports. The long duration of a cricket match can see players becoming uncomfortable with wearing the GPS vest (used by players at the time of interviews): *'it's a tight-fitting vest so a few of them don't like it, erm but I think the big issue we have is that its designed for rugby and football wearing something say for 80 90 minutes, these guys are wearing it for 6 hours and starting to get rashes and stuff' (P05).*

Pre-season preparations

Workload monitoring and adequately building bowling workloads through pre-season to ensure players are suitably prepared to meet the physical demands of the start of the competitive season was consistently the focus of discussion around pre-season preparations for all participants: *'I think the number of overs bowled in pre-season is a massive factor' (P01).* The need to also build intensity into preparations was acknowledged: *'I think there's a difference in competitive overs to net overs and warm up overs. I think the intensity of championship cricket is so much higher than 2nd eleven and their overs, you can prep all you want in terms of the amount of the overs you bowl in a net scenario, but when you get in that 1st game, you're going up another 10%, and its subconscious so actually getting them into that competitive mode I think it's just another step up' (P02).*

Sub theme: Challenges with pre-season preparations

Several challenges with building pre-season workload were consistently identified by different participants, with one practitioner admitting they *'come up with different theories each year' (S&CC06)*. Preparations often start with bowling indoors, on a different surface with shorter run-ups. This then progresses to bowling outside with some clubs using marquees to provide a longer (or full) run up to replicate distances often covered in matches: *'through pre-season bowling our biggest issue is like, where to bowl … so we have a little bit inside but we don't have a full run up … and then if you go outside its weather, so the issue being is that you're trying to build overs in March, but you can't guarantee you've got 20 good days in March' (P05).*

Club culture

How working relationships between people and departments can influence the effectiveness of output became apparent through the analysis. The culture of the club, and cricket as a sport, also emerged through the analysis.

Sub theme: Negative club culture

For some participants, it appeared it can be difficult for certain practitioners to effectively implement player monitoring efforts if their club management/coaches do not appreciate its importance and 'buy in' to its value: '*you are very limited in erm … not your ambitions as practitioners working in this environment but … you're limited by the buy-in from the coaching staff'' (P01)*. One practitioner shared the perspective of a coach and understood their frustrations: '*when talking around monitoring workloads because, if they're not seeing change (in injury trends) then why would you buy-in' (S&CC01)*. The attitude of coaches, players and cricket towards science and medicine were also mooted by several participants: '*probably players attitudes to science and medicine, coaches' attitude to science and medicine, I think cricket's attitude to science and medicine… I think cricket's attitude's changing' (P05)*. The increased professionalism of cricket was acknowledged but with the suggestion that for some, the *'old schoolness of the culture' (P06)* is holding some aspects of science and medicine practice behind.

Sub theme: Positive club culture

Player monitoring appeared effective when practitioners had a working relationship with coaches whereby suggestions could be made, and matters discussed. This insight emerged from a few of the participants. A common purpose also helped ensure actions, suggestions and discussions were guided by similar principles as one example illustrated: *'the nice thing this club has done is they've tried to explain to each player individually and as a group that everything is done to try and help us win' (P02)*. Building a positive culture shaped by shared and clear values takes a concerted effort that was believed to be beneficial for all involved: '*if you walk into an environment where you feel like, you know the club believe it, they invest in proper facility here for me as a player' (S&CC06)*.

5.4 Discussion

The aim of this study was to capture and quantify the current practices and perceptions of workload and player monitoring in elite men's senior cricket through a mixed methods design. Data harmonisation enabled collective insights to be drawn from the results. The survey identified and quantified injury risk factor perceptions and prevention initiatives with the interviews exploring in more detail current practices and perceptions of workload and player monitoring.

Previous research has identified an increased risk of injury for bowlers in cricket (Stretch 2003; Orchard et al. 2006; Mansingh et al, 2005; Frost and Chalmers, 2014; Orchard et al, 2016a), often focusing on the association of injury and workload, measured by overs bowled (Dennis et al., 2003; Dennis et al., 2004; Hulin et al., 2014; Orchard et al., 2015). . The importance of overs as a measure of workload was apparent in the survey responses, with it perceived by practitioners to be the top tool for assessing injury risk. This finding was supported by the results of the qualitative methods, with the importance of monitoring overs and workload also emerging in the interviews. The use of GPS to monitor physical load were consistency discussed by participants, as was the theme of pre-season preparations and the need to adequately build bowling workloads to ensure players are suitably physically prepared for the start of the competitive season.

The biggest insight overlap between the different data sets acquired by the mixed methods was around factors that impact effective workload and player monitoring. From the survey, the frequently endorsed factors (in order of accumulated points of importance) were player adherence, human resource, practical application of monitoring knowledge, theoretical understanding of monitoring and support from management. These factors contributed to three of the six core themes that consistently emerged from the interviews.

Previous injury was perceived to be the top intrinsic injury risk factor by practitioners involved in the study, which supports previous research in football and rugby (McCall et al., 2016; West et al., 2019). Consistent with previous findings also was physical fitness being perceived to an important intrinsic risk factor (McCall et al., 2016), with evidence starting to emerge around the link between well-developed physical fitness and better tolerance to higher workloads (Malone et al., 2019). Improved fitness could arguably allow players to better cope with what was perceived to be the most important extrinsic risk factors by practitioners in this study. These were reduced recovery time (which was also found in a study with football clubs included in the UEFA Elite Club Injury Study research initiative [McCall et al., 2016]), congested match schedule, and number of matches/minutes played, highlighting a potential area for a future preventative initiative.

The identification of possible injury risk factors that could inform injury preventative strategies is the second phase of O'Brien et al's (2019) three phase cycle for team-sport injury prevention (once the extent of the injury problem has been established in the first phase). Part of this second phase involves exploring potential barriers and facilitators to delivering injury prevention strategies, which the qualitative results of this study contribute towards. With physical fitness perceived to be an important injury risk factor, any potential preventative strategies developed in this area need to consider the culture of cricket that emerged through the interviews. The practitioners indicated that there is a transition of the culture within cricket, with increased professionalism and more appreciation/adoption of science and medicine in the game; however, this is not currently widespread and some players and coaches have not fully embraced science and medicine approaches, indicative of the 'old-school' culture of the sport as it was described by participants.

The importance of having 'buy-in' at all levels for effective player monitoring is a finding from this study that echoes previous research on factors influencing monitoring implementation (Saw et al., 2015). The results highlight a common purpose across the club can facilitate successful monitoring practices ensuring actions, suggestions and discussions are guided by similar principles. Player adherence to monitoring initiatives was found to be one of the top perceived factors that can impact effective player monitoring, which was also found to be a barrier to the implementation of injury prevention strategies in previous research (Saw et al., 2015; McCall et al., 2016). Communicating the value of any monitoring efforts is important for improving player 'buy-in' and subsequently adherence.

In Elite European football, a ‘lack of internal communication (i.e., between staff)’ was ranked the third most important extrinsic injury risk factor by practitioners (McCall et al., 2016). The results from the current study suggest the challenge for practitioners in domestic cricket, is highlighting and providing feedback on how exactly such monitoring efforts have prevented and subsequently reduced injury in the past, when coaches are seeing similar injury incidence each year. This would be despite continuous player monitoring with comparatively similar (or slightly less) cricket being played, as identified by previous research (Goggins et al., 2020a). However, it may be that injury rates are consistent because of the continuous efforts and a lack of monitoring would result in an increase in injury rates but this is just speculation and would be difficult to test.

The results highlight the need for clarity and greater understanding of the theoretical and practical application of monitoring for practitioners within cricket. This came out as one of the top factors influencing player monitoring in the survey, illustrated by one practitioner in the interviews who admitted they come up with different theories each year to developing and monitoring workloads. To illustrate, bowling workload has been shown to be an important factor within cricket (Orchard et al., 2009; Orchard et al., 2015; Warren et al., 2018; Tysoe et al., 2020), and featured heavily in both survey and interview responses in this study. Participants described widespread use of ACWR (Hulin et al., 2014; Hulin et al., 2016) to minimise injury risk (Gabbett, 2016), however, there is poor evidence to support ACWR as a risk factor for injury (Coyne et al., 2018; Impellizzeri et al., 2019), and it has been criticised for failing to account for the decaying nature of fitness and fatigue effects over time (Hawley, 2002). With the continued debate on suitable calculation methods the use of ACWR should continue to be tested with further investigation warranted into what acute and chronic time periods might be more appropriate for use in cricket (Tysoe et al., 2020). Given the common use of bowling overs, alternatives for monitoring workloads, such as ‘exponentially weighted moving averages’ [EWMA] (Williams et al., 2017), should also be explored in future research.

Although a strength of a mixed methods study is the ability to triangulate survey and interview responses that enhance the trustworthiness of the findings, there are limitations with both the quantitative and qualitative methods that need to be considered. Due to the structure of the survey, its construct validity cannot be tested as it is not measuring a theoretical construct but instead gathering information on a checklist of features for each club, with expectations this will differ between participants. Although the survey can be deemed to have reasonable face validity, this was not directly assessed. Furthermore, survey responses are based on perceptions and experiences of the sports practitioners, which may vary between the two roles held by the participants (physiotherapist and strength & conditioning coach) and the amount of experience of the practitioner garnered in that role and at their current club. Capturing responses from both the physiotherapist and strength & conditioning coach for each club somewhat mitigated these risks. Ensuring a broader perspective reduced the potential of over- or under-estimating risk factors that may arise from one point of view, although it must be noted, this was not always achieved. For the qualitative analysis, there was only one coder for the interview transcripts. The inductive approach adopted by this study involves a more organic and flexible coding process that can be undertaken by one researcher (Although in this study the defined themes were subsequently checked and validated by other co-authors). However, having multiple coders initially during analysis is deemed to strengthen the credibility of qualitative findings, providing the opportunity for coders to check for consistencies and discuss any inconsistencies until a consensus is reached (Lindblom et al., 2018). Although this was somewhat mitigated in this study, with defined themes subsequently checked and validated by co-authors.

Cricket as a sport presents distinct challenges that need to be considered for any research being developed in this area as well as the extent any findings can be generalised to other sports. During the season players spend a significantly larger proportion of their time in competitive matches as opposed to training, compared to other team sports such as rugby and football. Matches last hours and days as opposed to 80 or 90 minutes. This was apparent in the discussion around the use of GPS, where it was highlighted that wearing a tight-fitting vest for extended periods can be uncomfortable (typically during the longer First-Class cricket format, where a match is scheduled to last 4 days with approximately 6 hours a day played). This balance of exposure presents a challenge to practitioners in this setting when ensuring players are adequately prepared physically to manage the varying and unpredictable demands of the game, with reduced opportunity for recovery between matches in a typical week. In summary, the unique demands of cricket need to be explicitly considered within any injury prevention initiatives, and findings from other sporting populations are unlikely to translate directly to this setting.

5.5 Conclusion

This study aimed to capture and quantify the current injury risk factor perceptions and practice of player monitoring of sport practitioners in elite men's senior domestic cricket in England and Wales. The top perceived risk factors of previous injury, physical fitness, accumulated fatigue, reduced recovery time and training load support findings from previous research. Similarly communicating the purpose and value of player monitoring is important for buy-in and adherence to any monitoring initiatives, which can be facilitated through effective working relationships with key stakeholders. More needs to be done to support practitioners in cricket with appropriate player monitoring methods and analysis.

CHAPTER SIX

Injury and player availability in Women's International Pathway cricket from 2015 to 2019

6.1 Introduction

A relatively small number of players with variable athletic backgrounds and an emerging organisational structure within the professional women's game create unique challenges to keeping players healthy for effective athlete development. With any sport, player availability (through not being injured) is as important a factor in team sport success as player skill (Orchard, 2009), and injuries have a negative association with team and individual athletic achievement (Drew et al., 2016). Consequently, increased availability of team members increases the likelihood of team success, with preventative measures suggested as a priority for maximising performance (Drew et al., 2017).

Cricket injury epidemiology has previously focused on the more established men's game due to the infrastructure afforded to a long-founded professional sport. Yet, considering potential sex differences in biomechanics (Felton et al., 2019) as well as morphological and physical characteristics such as skeletal maturation, strength, physiological responses and adaptation (Stuelcken et al., 2007; Stuelcken et al., 2008) there is a need to establish a body of evidence specific to women's cricket.

To date, there has been limited research in women's cricket (Munro & Christie, 2018). Two recent studies have provided initial injury surveillance data from elite female Australian national and international cricketers over two seasons from 2014 to 2016 (Perera et al., 2019) and domestic T20 cricket (in 2016 and 2017) in England and Wales (Warren et al., 2019). Differences in the injury profiles emerged between the two papers, but as both studies did not adopt similar injury measures, it is not possible to effectively draw comparison between the two. Therefore, our understanding of injury patterns in women's cricket is still limited.

To add to this growing evidence base, the aim of this study is for the first time to describe the basic injury and illness epidemiology of an international women's cricket development pathway in England and Wales to understand what may influence availability in this unique context where players are contracted part-time. Specifically, it will focus on the consensus-recommended (Orchard et al., 2016b) incidence units of annual medical complaint incidence (per 100 players per year) to specific body regions, complaint type, mode of onset, activity at time of injury and complaint prevalence for activity and body region.

6.2 Methods

6.2.1 Participants

A total of 83 players were registered to an academy squad on the international development pathway over the four years, with an average 51 players each year. Registered players were contracted to the pathway on a part-time basis aged between 14-31 years (mean 19.75 ± 4.03). Each year on average, 37% (*n* = 19) of players were aged 17 and below, 49% (*n* = 25) aged 18-24, 10% (*n* = 5) aged 25-29 and 3% (*n* = 2) aged 30 and above.

6.2.2 Procedures

The current prospective cohort study encompasses four years (1st April 2015 – 31st March 2019 inclusive) of the England international women's pathway. This pathway is to develop players who have the potential to compete at an international level but are not yet part of the senior professional international team. It is made up of the England Women's Academy and Senior Academy squads. At the time of data collection there was no fixed playing schedule with competitive matches arranged each year.

Before the England and Wales Cricket Board (ECB) shared the injury surveillance data with the University research partner, the data was anonymised by the ECB England Women's Medical Services Lead. All players provided informed written consent for their data to be routinely collected and analysed by ECB and a University research partner (Appendix A), arranged in conjunction with the players' union (The Professional Cricketers Association; PCA). This was done at the time of registration and reviewed if there were any significant process or contractual changes during the year. Ethical approval was obtained from the University of Bath Research Ethics Approval Committee for Health (REACH) [reference: EP 17/18 111].

6.2.3 Study Outcomes

For this study, ECB medical staff working with the international pathway defined and recorded any medical complaint (injury or illness) reported by the player that resulted in them being either available with or without necessary modified activity (non-time loss) or completely unavailable (time-loss) for match selection during the year, regardless of whether a match was scheduled. The term 'medical complaint' adopted by this study is inclusive of both injury and illness (excluding mental health) in line with the updated consensus statement (Orchard et al., 2016b).

To adhere to consensus guidelines and allow flexibility for future comparison, two incidence units (one injury and one medical complaint), which included sudden-onset, impact/traumatic, gradual onset, insidious injuries and medical illness (where stated) were applied retrospectively for analysis (Orchard et al., 2016b):

1. Match injury incidence included all new and recurring time loss injuries (not illness) sustained during matches, reported for all phases (batting, bowling and fielding) with the unit of injuries per 1,000 player match days for all competition formats combined (First-Class, One-Day International and T20 cricket) due to the limited number of games in each format. Recurrence was defined by the practitioner as an injury of the same type, on the same side, in the same body region, in the same season as an injury from which a player has previously recovered (Orchard et al., 2016b).

Match injury incidence

$$= \frac{\text{Match time loss injuries}}{\text{Player match days}} \times 1000$$

2. Annual medical complaint incidence (for both injury and illness) was calculated from all new and recurring non-time loss and time loss medical complaints per 100 players per year. The consensus recommends this unit as it allows all complaints to be contained in one measurement (Orchard et al., 2016b).

Annual medical complaint incidence

$$= \frac{\text{All complaints}}{\text{Registered players}} \times 100$$

Complaint prevalence was calculated as the percentage of players who were either available for selection with or without modified activity (non-time loss complaint) or completely unavailable (time loss complaint) for participation. In line with consensus guidelines (Orchard et al., 2016b), both ‘match complaint prevalence’ and ‘general complaint prevalence’ were assessed. ‘Match complaint prevalence’ (the percentage of players unavailable for match-play because of injury or illness) was determined specifically for time loss complaints, calculated using the numerator of ‘missed player games’ and a denominator of total number of games multiplied by number of squad members.

Match complaint prevalence

$$= \frac{\text{Missed player games due to time loss injury}}{\text{((Total number of games) x (Number of squad members))}} \times 100$$

‘General complaint prevalence’ corresponds to the prevalence of medical complaints sustained during each year, reflecting the domestic cricket season in England and Wales from April 1st to March 31st the following year. It is presented as a percentage, representing the percentage of players either available (non-time loss complaint) or unavailable (time loss complaint) on any given day (not just match days), as a proportion of the total number of registered players. It was calculated by the numerator of total missed or modified days for all injuries and illness, with a denominator comprised of the total number of days in the surveillance period multiplied by the total number of registered players.

General complaint prevalence

$$= \frac{\text{Missed or modified days for all complaints}}{\text{((Total number of days) x (Number of registered players))}} \times 100$$

The availability status of each player was collected every contact day (e.g. match, camp, tour or training day) by medical staff working on the international pathway, using an Excel spreadsheet. There were four potential categories for a player: 1) No complaint reported full activity; 2) Complaint reported but no modified activity; 3) Modified activity; 4) Unavailable. Non-time loss complaints related to category 2 and 3, with time loss complaints coded as category 4. Categorisation included new and recurrent complaints, with each complaint requiring the squad physiotherapist to record body region and diagnosis based on the Orchard Sports Injury Classification System Version 10 (Rae & Orchard, 2007). Activity at time of injury (excluding illness), complaint mode of onset and type (e.g. ‘Match’, ‘Training’ or ‘Other’) were also recorded. The medical staff involved received training on categorisation with continual support provided by the England Women’s Medical Services Lead to maximise the reliability of the collected data.

6.2.4 Statistical analyses

Incidence and prevalence rates were summarised in Microsoft Excel with descriptive statistics based on means and 95% Poisson confidence intervals (CI).

6.3 Results

6.3.1 Injury incidence

There were 7.0 (95% CI 4.6-10.6) match time loss injuries per 1,000 player match days. Aside from injuries (excluding illness) marked as ‘Other’, which included such activities as ‘endurance training’ and those categorised as ‘other sport’ (i.e., injuries that happened outside of cricket but were reported to medical staff), fielding (in matches and training) resulted in the highest average overall and time loss injury incidence rates, followed by batting (table 6.1).

Table 6.1: Mean annual injury incidence rates (new and recurrent time loss and non-time loss injuries per 100 players per year) by activity at time of injury (excluding illness)

	Time Loss	Non-Time Loss	Total
Other	11.0 (7.4, 16.4)	67.3 (56.9, 79.6)	78.3 (67.1, 91.4)
Fielding	8.1 (5.0, 13.2)	48.3 (39.7, 58.8)	56.4 (47.0, 67.7)
Batting	6.4 (3.7, 11.0)	16.3 (11.6, 22.8)	22.7 (17.1, 30.2)
Bowling	5.7 (3.2, 10.0)	13.8 (9.6, 19.9)	19.5 (14.4, 26.5)
Wicket Keeping	0.0 (0.0, 0.0)	5.6 (3.1, 10.1)	5.6 (3.1, 10.1)
All injuries	**31.2 (24.5, 39.8)**	**151.3 (135.4, 169.1)**	**182.5 (164.9, 201.9)**

6.3.2 Complaint incidence

Medical complaints include injury (sudden-onset, impact/traumatic, gradual onset and insidious) and illness that was not necessarily sustained during matches or training but affects player availability. On average, most medical complaints occurred during training (fig 6.1). When comparing medical illness to body regions injured, illness was the complaint with the highest overall incidence, followed by hand and lower back injuries (table 6.2). The highest time loss incidence was reported for medical illness followed by thigh and lower back injuries (table 6.2).

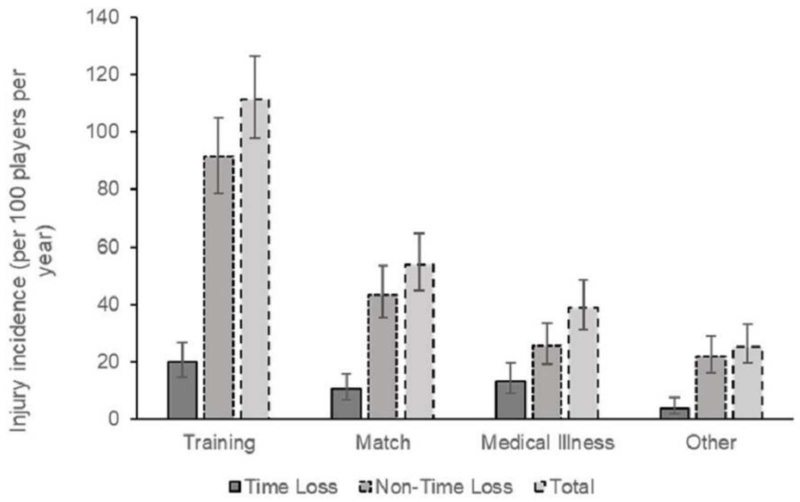

Figure 6.1: Mean annual complaint incidence rates (new and recurrent time loss and non-time loss medical complaints per 100 players per year) by problem type

Given the high incidence of medical illness, a further breakdown was explored to enhance understanding of these complaints. 62% of all medical illness complaints (time loss and non-time loss) related to two illnesses: Upper respiratory tract infections (URTI), which can affect sinuses, throat,

Table 6.2: Mean annual complaint incidence (new and recurrent time loss complaints per 100 players per year) by body region

	Time Loss	Non-Time Loss	Total
Medical illness	15.7 (11.1, 22.2)	29.3 (22.8, 37.7)	45.0 (36.7, 55.1)
Hand	2.8 (1.3, 6.2)	21.9 (16.3, 29.4)	24.7 (18.7, 32.6)
Lower back	5.8 (3.2, 10.2)	18.8 (13.7, 25.8)	24.5 (18.6, 32.3)
Thigh	6.4 (3.7, 11.0)	15.9 (11.3, 22.4)	22.2 (16.6, 29.6)
Knee	3.9 (2.0, 7.8)	14.9 (10.4, 21.3)	18.9 (13.8, 26.0)
Elbow	1.0 (0.3, 4.0)	13.2 (9.1, 19.1)	14.2 (9.9, 20.3)
Leg	1.3 (0.4, 4.0)	12.0 (8.1, 17.8)	13.4 (9.3, 19.4)
Shoulder	0.0 (0.0, 0.0)	12.0 (8.0, 17.9)	12.0 (8.0, 17.9)
Hip	0.9 (0.2, 3.6)	9.8 (6.4, 15.0)	10.7 (7.1, 16.1)
Ankle	1.3 (0.4, 4.0)	8.9 (5.6, 14.1)	10.2 (6.7, 15.6)
Foot	1.3 (0.4, 4.0)	7.3 (4.5, 11.9)	8.6 (5.5, 13.5)
Head & Face	6.0 (3.4, 10.6)	2.2 (0.8, 5.9)	8.2 (5.0, 13.4)
Thoracic	1.1 (0.3, 4.4)	5.9 (3.4, 10.4)	6.9 (4.1, 11.7)
Neck	0.0 (0.0, 0.0)	6.4 (3.7, 11.0)	6.4 (3.7, 11.0)
Wrist	0.0 (0.0, 0.0)	3.4 (1.6, 7.1)	3.4 (1.6, 7.1)
All complaints	**47.4 (38.9, 57.8)**	**182.1 (164.5, 201.5)**	**229.4 (209.6, 251.1)**

airways or lungs, accounted for 38% and gastrointestinal tract infection (GTI)/"stomach bugs", accounted for a further 24% of all illness complaints (table 6.3).

Gradual onset, followed by impact/trauma, was the mode of onset that yielded the highest overall complaint incidence during the study (table 6.4).

6.3.3 Injury prevalence

Overall average match injury prevalence was 4.1% (95% CI 2.7-6.2), with 95.9% of players available for selection on any given match day (from all medical complaints). Focusing on all injuries (not illness), aside from those marked as 'Other', fielding injuries had the highest overall injury prevalence (2.3%). Bowling resulted in the highest average time loss prevalence, with an average of 0.6% of players being completely unavailable due to injuries sustained whilst bowling (table 6.5).

Table 6.3: Breakdown of all medical illness complaints over the four-year study period

	Number of injuries			
Medical Illness	Time loss	Non-time loss	%	Total
URTI	8	27	38%	
GIT/"stomach bug"	12	10	24%	
Migraine/headache	1	4	5%	
Ear-related complaints	2	1	3%	
Menstrual-related complaints	1	2	3%	

Table 6.4: Mean annual complaint incidence rates (new and recurrent time loss and non-time loss complaints per 100 players) by mode of onset

	Time Loss	Non-Time Loss	Total
Gradual onset	10.8 (7.2, 16.3)	65.8 (55.6, 77.9)	76.6 (65.5, 89.6)
Impact/traumatic	12.7 (8.7, 18.5)	38.5 (30.8, 48.1)	51.2 (42.2, 62.0)
Medical illness	16.9 (12.1, 23.7)	30.8 (24.1, 39.4)	47.6 (39.1, 58.0)
Sudden onset no trauma	7.2 (4.3, 12.2)	40.2 (32.5, 49.7)	47.4 (38.9, 57.7)
Insidious	0.0 (0.0, 0.0)	6.2 (3.6, 10.7)	6.2 (3.6, 10.7)
All complaints	**47.5 (39.0, 57.9)**	**181.6 (164.1, 201.0)**	**229.0 (209.2, 250.6)**

Table 6.5: Mean general annual injury prevalence rates by activity at time of injury (excluding medical illness)

	Injured available	Injured modified activity	Injured unavailable	Total prevalence
Other	2.0% (1.7, 2.4)	0.3% (0.3, 0.4)	0.4% (0.3, 0.6)	3.1% (2.7, 3.6)
Fielding	1.4% (1.1, 1.7)	0.2% (0.2, 0.2)	0.5% (0.3, 0.8)	2.3% (1.9, 2.8)
Bowling	0.4% (0.3, 0.6)	0.1% (0.1, 0.1)	0.6% (0.3, 1.1)	1.1% (0.8, 1.5)
Batting	0.4% (0.3, 0.6)	0.1% (0.1, 0.1)	0.4% (0.2, 0.7)	0.9% (0.7, 1.2)
Wicket-Keeping	0.2% (0.1, 0.4)	0.0% (0.0, 0.0)	0.0% (0.0, 0.0)	0.2% (0.1, 0.4)
All injuries	**4.4% (3.9, 4.9)**	**0.7% (0.6, 0.8)**	**1.9% (1.5, 2.4)**	**7.7% (7.0, 8.5)**

6.3.4 Complaint prevalence

Of all medical complaints, lower back injuries had the highest average annual complaint prevalence (1.3% overall prevalence with 0.6% of players completely unavailable on any given day during the year due to lower back injuries), followed by medical illness and knee injuries (table 6). Overall, approximately 8.4% of players were impacted by medical complaints (were available, had modified activity or were unavailable), with an average 2.3% of players completely unavailable, on any given day during the year.

Table 6.6: Mean general annual complaint prevalence rates by body region (including medical illness)

	Injured available	Injured modified activity	Injured unavailable	Total prevalence
Lower back	0.6% (0.4, 0.8)	0.1% (0.1, 0.1)	0.6% (0.3, 1.1)	1.3% (1.0, 1.7)
Medical illness	0.6% (0.5, 0.8)	0.2% (0.2, 0.3)	0.4% (0.3, 0.6)	1.2% (1.0, 1.5)
Knee	0.5% (0.3, 0.7)	0.1% (0.1, 0.1)	0.3% (0.2, 0.6)	0.8% (0.6, 1.1)
Hand	0.5% (0.4, 0.7)	0.1% (0.1, 0.1)	0.1% (0.0, 0.2)	0.8% (0.6, 1.1)
Elbow	0.6% (0.4, 0.9)	0.1% (0.1, 0.1)	0.1% (0.0, 0.4)	0.7% (0.5, 1.0)
Thigh	0.4% (0.3, 0.6)	0.1% (0.1, 0.1)	0.2% (0.1, 0.3)	0.7% (0.5, 0.9)
Shoulder	0.5% (0.3, 0.7)	0.0% (0.0, 0.0)	0.0% (0.0, 0.0)	0.5% (0.3, 0.7)
Head/Face	0.0% (0.0, 0.0)	0.0% (0.0, 0.0)	0.4% (0.2, 0.7)	0.4% (0.2, 0.7)
Leg	0.3% (0.2, 0.4)	0.1% (0.1, 0.1)	0.0% (0.0, 0.0)	0.4% (0.3, 0.6)
Hip	0.3% (0.2, 0.5)	0.1% (0.1, 0.2)	0.1% (0.0, 0.4)	0.4% (0.3, 0.6)
Ankle	0.2% (0.1, 0.3)	0.1% (0.1, 0.2)	0.1% (0.0, 0.3)	0.4% (0.3, 0.6)
Foot	0.2% (0.1, 0.3)	0.0% (0.0, 0.0)	0.1% (0.0, 0.3)	0.3% (0.2, 0.5)
Wrist	0.1% (0.0, 0.2)	0.0% (0.0, 0.0)	0.0% (0.0, 0.0)	0.2% (0.1, 0.4)
Thoracic	0.1% (0.1, 0.2)	0.0% (0.0, 0.0)	0.0% (0.0, 0.0)	0.2% (0.1, 0.3)
Neck	0.1% (0.1, 0.2)	0.0% (0.0, 0.0)	0.0% (0.0, 0.0)	0.1% (0.1, 0.2)
All complaints	**5.2% (4.7, 5.8)**	**0.9% (0.8, 1.0)**	**2.3% (1.9, 2.8)**	**8.4% (7.7, 9.2)**

6.4 Discussion

The aim of this study was to describe for the first time the basic injury and illness epidemiology of an international women's cricket academy pathway, to begin to understand the injury and illness patterns that may impact player availability in this unique context. The study focused on exploring complaint type, activity at time of injury, body region affected and mode of onset from injury and illness surveillance conducted over four years. Most injuries were sustained during activities marked as 'other' (which included such activities as 'other sport', as some of the players are multisport athletes, and 'endurance training'), followed by fielding. Fielding was the activity with the highest general annual injury prevalence, whilst bowling resulted in the most players being completely unavailable on any given day of the year. Of all medical complaints, most occurred during training, with illness followed by hand injuries having the highest overall average annual incidence rates, whilst lower back injuries had the highest annual time loss complaint incidence and general prevalence rates. Gradual onset was the mode of onset with the highest overall average complaint incidence rates, with illness having the highest annual time loss incidence rates.

The higher proportion of complaints occurring during training as opposed to matches reflects the balance of exposure in this setting. This in part may explain the high overall incidence of gradual onset complaints found in this study, which may possibly be prevented through appropriate physical preparedness and effective workload monitoring (Warren et al., 2019). Players can start the pathway with a variable bowling workload history and may not have maintained the necessary chronic workload to manage the demands of a year-round training, touring and competitive schedule. The part-time nature of player contracts and lack of consistent fixtures is a challenge for players and practitioners, not least because part-time players experience a high proportion of time loss through medical illness and injuries sustained during 'other' activities.

The high incidence of medical illness (relative to other complaints) in this study seems to be a distinct feature of the women's cricket international pathway in comparison to findings from previous prospective cohort injury surveillance research published in both men's and women's cricket (Orchard et al,. 2006; Frost & Chalmers, 2014; Orchard et al., 2016a; Warren et al., 2019). Although caution needs to be exercised when comparing to previous research, given the part-time nature of players involved in this study, it does highlight an area that could be targeted for prevention. Over half of the medical illness complaints resulted from two conditions (upper respiratory tract infections and gastrointestinal tract infection/"stomach bugs"), with travel and competition shown to be risk factors for these types of complaints in elite sport (Soligard et al., 2016; Svendsen et al., 2016), factors pathway cricketers experience regularly. Significantly increased training and playing loads in relatively immature athletes has also been shown to predispose an increased risk of infection (Schwellnus et al., 2016). Encouragingly, the incidence of such complaints can be lowered through preventative measures. Infection control initiatives and/or education around correct hand washing techniques (Ejemot-Nwadiaro et al., 2015), use of anti-bacterial gels/wipes (Ranchordas et al., 2016), nutrition (Walsh et al., 2016; Gleeson, 2016; Bermon et al., 2017) and healthy sleep practices (Ranchordas et al., 2016; Walsh et al., 2016) have been found effective in reducing these types of illnesses and are recommended.

It is important to establish a body of evidence specific to women's cricket in order to guide identification of injury risk factors and mechanisms that can then inform preventative measures tailored to this environment. The high time loss complaint incidence and prevalence rates for thigh and lower back injuries (relative to other body regions) observed in this study follow similar trends to those in the men's game (Stretch, 2003; Mansingh et al., 2006; Orchard et al., 2006; Frost & Chalmers, 2014; Orchard et al., 2016a), particularly with lower back complaints (most notably lumbar spine stress injuries) resulting in the most days lost. Injuries to this body region are especially apparent in bowlers (particularly fast bowlers), the activity that results in the highest time loss in the men's game (Stretch, 2003; Mansingh et al., 2006; Orchard et al., 2006; Frost & Chalmers, 2014; Orchard et al., 2016a). The unique biomechanical demands of fast bowling result in players being particularly susceptible to lumbar spine injuries in part due to the extreme trunk lateral flexion postures required (Bayne et al., 2016). With a younger age being shown to be an important risk factor in fast bowling lumbar spine injuries (Johnson et al., 2012), the younger profile of the current sample could present an increased injury risk for those on the pathway.

This study begins to establish the extent of the injury (and illness) problem for a women's pathway development programme at the highest international level, as outlined in the first phase of O'Brien et al.'s (2019) three phase cycle for team-sport injury prevention. The second phase of this model aims to establish the risk factors and mechanisms of these complaints that can then inform preventive strategies, with this study already identifying medical illness as a potential preventative area for the women's pathway. Aside from the high thigh complaint incidence rates, with hamstring injuries common in sports involving high speed running, accelerations and decelerations (Croisier et al., 2008; Williams et al., 2013), the unique risk to cricket seem to be lumbar spine injuries that should be a priority for future research in this area.

As with any injury surveillance study there are limitations that need to be considered. The unique context of an international pathway, where players are contracted on a part-time basis, may limit the generalizability of the findings to other women's cricket settings. Players often come onto the pathway from the national domestic county system, where there is historically absent or inconsistent medical and strength and conditioning support for the women's game. This results in many athletes starting the pathway with an injury-related problem that is only identified when they have access to the improved medical infrastructure afforded to the international pathway. This is particularly pertinent for overuse injuries, which are sometimes not apparent until players start up playing again and therefore not necessarily picked up by the medical screening undertaken before a new player joins the pathway. In some way, this may overestimate the current injury problem with new injuries surfacing for a player on the pathway that are actually pre-existing injuries from the domestic county system. The increased professionalisation of the sport, reflected by the upcoming incorporation of a more professional domestic structure, should help in ensure better player monitoring across all levels of the game to help mitigate this risk. Furthermore, the high incidence and prevalence of injuries from 'other' activities is an additional limitation of this study and a category that needs to be expanded to provide additional detail for these injuries that can better inform future prevention strategies.

6.5 Conclusion

This study aimed to describe for the first time the basic injury and illness epidemiology of an international women's cricket pathway. Some findings supported themes that have emerged from previous injury surveillance research in the men's game, which could reflect some of the injury risk associated with cricket as a sport, regardless of the sex of the participants. The study also looked to understand the factors that can affect player availability in this unique development context where players are contracted part-time. The high occurrence of medical illness and injuries arising from 'other' activities are a challenge for the players and sport practitioners involved on the pathway and could highlight an area for future investigation and prevention.

CHAPTER SEVEN

Detecting injury risk factors with algorithmic models in elite women's pathway cricket

7.1 Introduction

Injuries occur because of complex and non-linear interactions amongst multiple variables. However, even with the use of more sophisticated statistical approaches, it can be difficult to fully capture their dynamic and multiplex nature (Ruddy et al., 2019). It has been proposed algorithmic modelling may provide a more accurate and informative alternative to conventional data model approaches (Breiman, 2001). Data model approaches include traditional regression models, whereby the values of the parameters in question are estimated from the data, and the model is then used for information and/or prediction (Breiman, 2001). Conversely, algorithmic models treat the data mechanism as unknown. This includes supervised learning techniques, which are a type of machine learning method able to account for the kind multifaceted interactions found between injury risk factors (Bittencourt et al, 2016). Commonly used supervised learning techniques are decision tree and random forest classifiers.

Initial studies attempting to predict sporting injuries with supervised learning techniques have had mixed success. A study in Australian football demonstrated similar predictive power to a random coin toss, with a poor area under the receiver operating characteristic curve median range of 0.52 to 0.58 (Ruddy et al., 2017). A model developed in Spanish soccer demonstrated better predictive power (area under the receiver operating characteristic curve [AUC] = 0.84), although this study had a smaller sample and the authors acknowledged the complexity of the final model involving 10 different classifiers and 66 predictors (Ayala et al., 2019). Another model with reasonable predictive power (AUC score of 0.88) was developed in professional soccer, with only three variables contributing to the best performing classifier, out of 42 predictor variables included in the models (Rossi et al., 2018). Given their previous limited success in predicting injury, the value of such approaches might not necessarily be in the more conventional application of predicting injuries, but as a useful way to explore and extract the most important risk factors associated with injury (Jauhiainen et al., 2020). It has been suggested conventional statistical approaches can be used to inform algorithmic models (Ruddy et al., 2019), but the reverse could also be true, with the best solution (for a given research question) sometimes being a combination of approaches (Breiman, 2001).

The aim of the present study was to conduct an exploratory analysis to investigate how algorithmic models may be able to identify important risk factors for injury in an international women's cricket development pathway in England and Wales, which may otherwise not have been apparent. More conventional data models were then used to assess the association between these risk factors and injury.

7.2 Methods

7.2.1 Setting

This prospective cohort study encompassed 17 months (1st April 2018 – 31st August 2019 inclusive) of the ECB women's international development pathway. This pathway is to develop players who have the potential to compete at an international level but are not yet part of the senior professional international team. It is made up of the England Women's Academy and Senior Academy squads. At the time of data collection there was no fixed playing schedule, but competitive matches were irregularly scheduled each year.

7.2.2 Participants

Players registered on the England and Wales Cricket Board (ECB) women's international development pathway were included in the study (*n* = 17). Registered players were contracted to the pathway on a part-time basis and were aged between 14-23 years (mean 18.2 ± 1.9) at the start of the study period. The players were classified as 'youth' if they were under the age of 18 (*n* = 7) and 'adult' if aged 18 years and above (*n* = 10). Of the group, 29% (*n* = 5) were classified as pace bowlers (an approach to bowling where the ball is delivered at high speeds), 59% (*n* = 10) spin bowlers (a technique where the ball is delivered slower than a pace bowler, with the potential to change direction when it hits the ground) and 12% (*n* = 2) all-rounders (who are proficient at both bowling and batting), with all participants batting when required.

7.2.3. Procedures

This prospective cohort study encompassed 18 months (1st April 2018 – 31st August 2019 inclusive) of the ECB women's international development pathway. This pathway is to develop players who have the potential to compete at an international level but are not yet part of the senior professional international team. It is made up of the England Women's Academy and Senior Academy squads. At the time of data collection there was no fixed playing schedule, but competitive matches were irregularly scheduled each year.

Institutional ethics approval was obtained for this study. All players provided informed written consent (assent and parental consent was also obtained for players under 18 years) for their data to be routinely collected and analysed by ECB and a University research partner.

7.2.4 Study outcomes

For this study, ECB medical staff working with the international pathway defined and recorded any injury that resulted in a player being either available with or without necessary modified activity (non-time loss) or completely unavailable (time-loss) for match selection during the year, regardless of whether a match was scheduled. Medical illnesses were also recorded but not included in this study as such complaints were deemed independent to injury risk factors. The availability status of each player was collected every contact day (e.g. match, camp, tour or training day) using an Excel spreadsheet. Categorisation included new and recurrent complaints, with each complaint requiring the squad physiotherapist to record body region and diagnosis based on the Orchard Sports Injury Classification System Version 10 (Rae & Orchard, 2007).

A range of physical profiling measures (descriptions provided in Appendix F) were collected by ECB Science & Medicine staff each year in January, June and October. Daily load data was collected throughout the year using a standardised data collection form completed by the player, strength & conditioning coach, and/or physiotherapist. Load data included a measure of the number of balls bowled (with six balls equating to one ‘over’) for both matches and training, and a total load calculated by the duration (in minutes) of each training session with a session rating of perceived exertion (sRPE) from 0 to 10 [0 being ‘rest’ and 10 being ‘my hardest ever effort’] (Foster et al., 2001). Training sessions for this total load included strength & conditioning (speed, strength, robustness, endurance, mobility) and skill (batting, bowling and throwing/fielding) sessions.

Several load monitoring measures were assessed for this study. A differential load measure (both linear and polynomial) originally proposed by Lazarus et al (2017) and shown to be a potential viable alternative to the often used ‘acute:chronic workload ratio’ (ACWR) in male fast bowlers (Tysoe et al, 2020), was calculated. The ACWR has previously been used in cricket injury research to explore the association between injury risk and load (Hulin et al., 2014), but there is poor evidence to support ACWR as a risk factor for injury (Coyne et al., 2018; Impellizzeri., 2019), and a number of methodological concerns with this metric have been raised (Wang et al., 2020). Differential load represents the smoothed rate of change in load from one week to the next, with a 7 day time constant used, as this was the best performing differential load time window when a variety (time constants of 7, 14, 21 and 28 days) were tested previously (Tysoe et al., 2020). A 7-day exponentially-weighted moving average (EWMA) of just bowling overs was also calculated (for comparison against the total load measure), along with a measure of the number of consecutive days bowled.

7.2.5 Statistical analyses

Descriptive statistics

Injury data was summarised in Microsoft Excel with descriptive statistics based on means and standard deviations.

Supervised learning techniques

All estimations were made using R (version 3.6.0, R Foundation for Statistical Computing, Vienna, Austria). Outliers over 3 standard deviations (SD) higher on load measures and any physical profiling factors that had over 25% missing data (deemed as a substantial cut-off due to the model omitting all accompanying data for any missing values, which would greatly reduce the overall number of data points in the model) were removed. Two different supervised learning techniques were conducted in this study using the *Rattle* package (Williams et al., 2020): a decision tree and random forest. The package includes ten-fold cross validation, which was used for model parameter optimisation on randomly selected training data (comprising 70% of the total). The model was validated using the remaining testing (30%) data. Model performance was measured by the probability a positive case will be ranked higher than a negative case, visualised as a receiver operator characteristic (ROC) curve, with the degree of separability represented by a value known as area under the curve (AUC). The higher the AUC (between 0 and 1) the better predictive power of the model, with 0.5 indicating prediction is no better than random chance (Ruddy et al., 2017) and 1 representing perfect prediction (Bahr, 2016).

All continuous data was standardised before building the predictive models by converting to within-individual z scores for the load measures and within-team z-scores for the physical profiling factors. Standardisation is common practice when using machine learning techniques as models can be sensitive to different ranges and magnitudes of predictor variables (Han & Kamber, 2006). Players were assigned a numerical code for identification purposes, which was labelled as such in the models, so it was not included as an input variable.

As traditional algorithms used in decision trees and random forest can also favour correlated predictor variables, both techniques were also run with conditional algorithms that have been suggested to provide a fairer means of comparison to help identify truly relevant predictor variables (Strobl et al., 2008). The AUC of both traditional and conditional algorithms was reported to see evaluate model performance. The aim of the study, however, was not to evaluate the predictive power of each model, but instead identify which risk factors consistently made meaningful contributions across the different models.

Generalised liner mixed effect models

The important injury risk factors identified by the supervised learning techniques, were included in multivariate analyses to identify the overall best-fitting model, as determined by the GLMERSelect stepwise selection procedure (Newbold, 2020). The model-selection routine starts with the most complex fixed-effects structure possible (given the specified combination of explanatory variables and their interactions), and then performed backward stepwise selection to obtain the minimum adequate model. Polynomial and interaction terms were evaluated in this process. Separate generalised linear mixed-effect models (GLMM) were then used to model the association between the risk factors and injury risk, undertaken using the *lmer* package (Bates et al., 2020). Fixed effects in the model were the intercept and load/profiling measure, with the square of the measure included to estimate the mean quadratic, where appropriate. A random effect was included for the interaction of player identity and the respective load measure. The different models were evaluated and compared using conditional r-squared and the Akaike Information Criterion (AIC) provided by the *performance* package (Lüdecke et al., 2020). When undertaking a study like this on developing a risk prediction model, the Transparent Reporting of a multivariable prediction model for Individual Prognosis or Diagnosis (TRIPOD) guidelines should be followed to ensure the usefulness of the prediction models studied can be adequately assessed (Grant et al., 2018). TRIPOD recommendations were developed in 2015 (Moons et al., 2015) and designed to improve the quality of risk prediction model research.

7.3 Results

7.3.1 Descriptive statistics

A total of 6,027 player days were included in the study (mean 355 ± 153 days/player). There were 50 injuries recorded for 16 (94%) players, with 1 (6%) remaining injury free. The 50 injuries consisted of 26 (52%) injuries to the upper extremity and 24 (48%) to the lower extremity.

7.3.2 Supervised learning techniques

Decision tree

A traditional algorithm decision tree with a minimum of 20 splits and 7 variables allowed in any leaf, with a maximum depth of 30, including 1,064 observations from 42 input variables, found 2 rules for predicting injury:

1. A player with a broad jump average z-score < -0.71, with a smoothed differential 7-day load z score < -0.71.
2. A player with a broad jump average z-score < -0.71, with a smoothed differential 7-day load z score >= -0.71 and a smoothed differential 7-day load z score >= 2.20

A conditional algorithm decision tree also found 2 (but different) rules for predicting injury:

1. A broad jump average z-score <= -0.81
2. A broad jump average z-score > -0.81 and right-side dorsiflexion lunge test z score <= -2.30.

When evaluating the model performance on the testing data set (30% of the data randomly split) the conditional algorithm (AUC of 0.57) and traditional algorithm (AUC of 0.57) both performed poorly.

Random Forest

The best performing random forest model had 100 trees with 8 variables tried at each split and included 1,064 observations (null values were excluded) from 47 input variables. When evaluating model performance on the testing data set, the conditional algorithm (AUC of 0.72) performed similar to the traditional algorithm (0.71), mostly in correctly classifying instances of no injury, which was the majority of the dataset.

The five variables that scored highest for importance from the traditional and conditional algorithm random forests are shown in table 7.1 and figure 7.1, respectively. Smoothed differential 7-day load was also found to be important variables in both random forest types, with average broad jump score also featuring in the traditional algorithm random forest.

Table 7.1: Top 5 important variables for traditional algorithm random forest

Factor	No injury	Injury	MeanDecreaseGini	MeanDecreaseAccuracy
Differential 7-day (poly)	5.71	8.56	6.33	8.46
Broad jump average	2.30	4.11	1.47	3.93
Triple hop average (right)	2.41	1.33	0.28	2.58
Single leg hop (left)	2.00	1.08	0.16	2.28
40 m speed	2.13	1.19	0.29	2.28

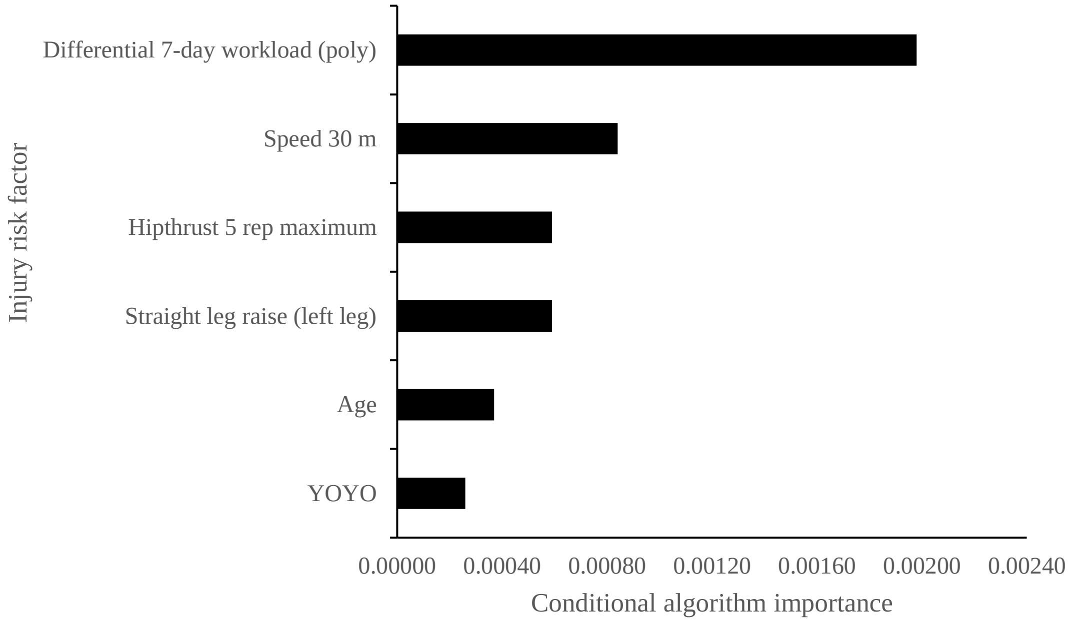

Figure 7.1: Top 5 important variables for conditional algorithm random forest

7.3.3 Generalised linear mixed effect models

From the factors identified as important by the supervised learning techniques, the backward stepwise selection procedure proposed a final model that contained the following factors: Differential 7-day load, broad jump average, 30 m speed, 40 m speed, right-side dorsiflexion lunge and left leg single leg hop.

Five different generalised linear mixed effect models were run to assess the association of the various risk factors and injury risk, to find the best model fit (model outputs and performance comparison provided in Appendix G). A model (AIC = 813.92, conditional r-squared = 0.67) containing polynomial smoothed differential 7-day load ($P < 0.001$), average broad jump scores ($P < 0.001$) and 30 m speed ($P < 0.001$) provided the best overall model fit.

A change in within-athlete smoothed differential 7-day load above or below 2 SDs from the mean was associated with increased injury risk, with a smaller effect for lower average broad jump scores and slower 30 m speed (fig 7.2).

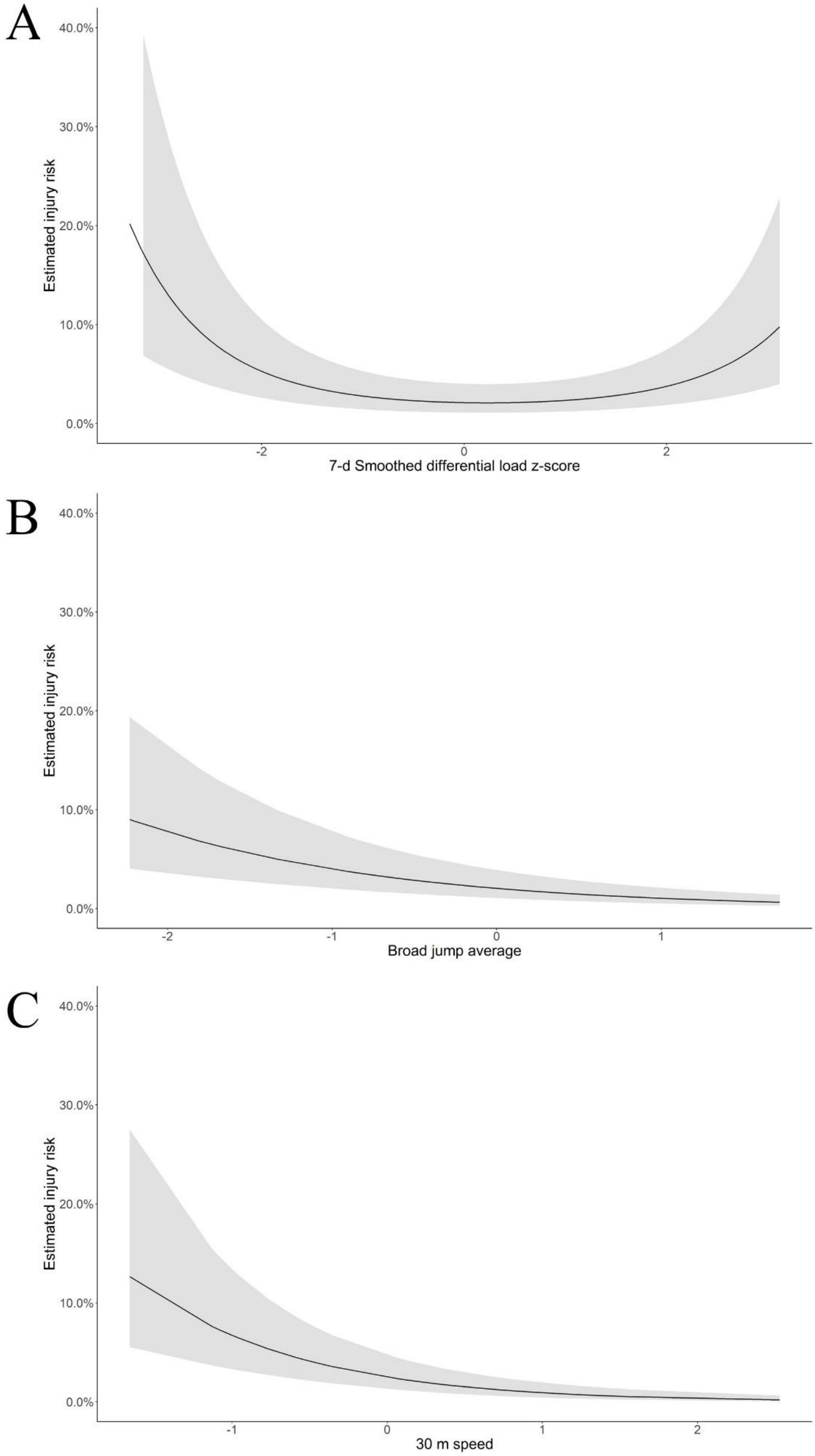

Figure 7.2: Associations between injury risk and predictor variables: A) smoothed differential load; B) broad jump performance; and C) 30 m speed

7.4 Discussion

This is the first study to explore the application of algorithmic models to identify key risk factors in cricket that may otherwise not have been apparent, then assess their association (using data models) with injury risk. The application of these techniques did find novel risk factors. The best performing predictive model included 7-day differential load, average broad jump score and 30 m speed that explained 67% of variance in injury.

The smoothed 7-day differential load had a polynomial relationship with injury risk, with an increased injury risk associated with a 2 to 4 standard deviation increase above or below a player's mean. This finding lends support to previous research that highlighted the need to pay special attention to bowlers returning from a period of unloading (Tysoe et al., 2020). These findings also demonstrated that the sRPE load measure had a stronger association with injury (through its greater contribution to the models) than the number of overs bowled. The sRPE load measure is likely to better capture the 'total load' undertaken by players (i.e., beyond bowling workloads), which may explain its greater sensitivity to injury risk (Hulin et al., 2014). Data from this measure may be enriched further by combining it with Global Positioning System (GPS) data, which has been effectively used in cricket to highlight the differing physical demands between playing position (Peterson et al., 2010) and match formats (Peterson et al., 2011).

The importance of broad jump performance and 30 m speed as injury risk factors emerged from the findings of this study, albeit with smaller effects on injury risk than differential load. This insight may help practitioners prioritise risk factors in this this setting. The importance placed on lower extremity factors perhaps reflects the consistently high incidence of thigh injuries in cricket injury surveillance research (Orchard et al., 2016; Goggins et al., 2020a; Goggins et al., 2020b). The broad jump test assesses lower limb explosive power (Moresi et al., 2011) and may be a useful practical measure for practitioners in this context. In a sample of collegiate women soccer players, 10 and 30 m speed were shown to be (one of multiple factors) negatively correlated with lower body strength (Anderson et al., 2018). Well-developed lower body strength, along with repeated-sprint ability and speed, have been shown to be associated with better tolerance to higher workloads and reduced risk of injury in a sample of amateur hurling athletes (Malone et al., 2019). As these previous studies include collegiate and amateur samples, it would be worthwhile for future research to ascertain whether similar associations are found with elite players where there would be arguably less variation in lower body strength as there might be with amateur samples. The associations found in this study were arrived at through a statistical process and provides a framework on how such techniques can be applied in other samples to identify novel risk factors pertinent to a given context.

The aim of the study was to explore which factors may be consistently associated with injury risk and not to use machine learning to necessarily predict injuries, but the predictive performance of the models was also evaluated. Similar to previous research, the supervised learning models in this study were unable to predict injuries with an AUC range of 0.57 – 0.71 for the traditional algorithm, compared to a median AUC range of 0.52 – 0.58 found in previous research that aimed to predict hamstring strain injuries in Australian football (Ruddy et al., 2017). Also, in line with previous research, of all the factors included in the models, only a limited number actually contributed to the best performing models (Rossi et al., 2018). The exact nature of the potential association between broad jump scores, 30 m speed and injury warrants exploration in future research. Further validation on the importance of these factors is also needed, with low model sensitivity and specificity, reflected by the poor AUC range. While researchers continue to explore how these supervised learning techniques can be best utilised in sports injury, such predictive models alone, do not currently have practical value for injury management practitioners.

The extent to which the findings of the current study can be generalised to other cricket playing populations is a limitation of the current study. Given the nature of data collection and the algorithmic models used, these findings may only be relevant to the sample of the study and other contexts that share similar characteristics. Being part of the international development pathway, the average player age for this sample can be younger than a sample of more senior players. This may affect the predictor variables selected by the models, and injury types that could be specific to this context. Prospective validation is needed to ascertain the credibility of these findings and the importance of these factors.

Other limitations that need to be considered are the inclusion of both time loss and non-time loss injuries. Including just time loss injuries may improve the accuracy of the models to identify the factors that are most pertinent in the development of more severe injuries. However, there is a lack of knowledge about the extent to which non-time loss injuries may interact or potentially contribute to the development of a subsequent time loss injury and only including those injuries that resulted in time loss may not fully capture the true burden of injuries (Ranson & Gregory, 2008). Consequently, all injuries were included in the analysis in this study, with the aim of providing as much data as possible for the algorithmic models. Furthermore, even though data was collected over a reasonable time period, there is still only a small number of players and injuries included in the sample with complete data for every measure not available for every player. This context is needed when considering the results and some degree of caution is recommended when interpreting the outcomes with the potential for model overfitting. A considerable limitation when using supervised learning techniques with injury risk is the amount of data required for these methodologies to make meaningful inferences (Carey et al., 2018).

Linear mixed models and machine learning techniques are complex and can have a high range of variability, which can raise questions on the reproducibility of the results (Renard et al., 2020). Predictive models are dependent on the predictors used in the training process and operators who wish to replicate the results of any predictive model, must follow the same assessment methodologies used in that study (Ayala et al., 2019). The potential operator variability bias needs to be considered in relation to the findings of the current study for both the supervised machine learning and linear mixed models. Firstly, the ability of the same operator to come up with a similar result on a second measurement performed on the same sample (intra-operator variability). Second is the ability of a different operator to come up with the same measurement (inter-operator variability). These components of variability can be quantified by a calculation of measurement error, to which several options are available and widely used in medical literature (Popovic & Thomas, 2017). Future research that develops models to measure risk in this area should aim to include an assessment of variability in their results, as a part of quality control and to add trustworthiness to the data reported.

7.5 Conclusion

Overall, this study aimed to explore how algorithmic models might help identify important injury risk factors that may not otherwise have been apparent, with their association with injury then assessed with more conventional data models. The methodology provides a framework for these techniques to be applied to explore uncovering novel injury risk factors in other settings, with the findings having potential to inform and guide practice, by identifying the most pertinent factors. In this sample of elite female cricketers, both high and low values of differential load were found to be associated with injury risk. Average broad jump scores and 30 m speed also contributed to the predictive models and so future research should aim to validate the importance of these factors and better understand their exact association with injury risk.

CHAPTER EIGHT

Discussion

8.1 Introduction

The aim of this thesis was to explore the injury profile of men's and women's cricket in England and Wales, focusing on the domestic county game and international pathway respectively, to inform future prevention strategies. Research questions were formed in Chapter 1 to achieve this aim, with Chapters 3-7 addressing these questions. The aim of this chapter is to summarise the main research findings of the thesis and discuss how they have addressed the research questions. The original and significant contribution to existing knowledge will also be highlighted along with a discussion on the strengths and weaknesses of the methodology deployed in this work. Practical implications will also be explored and recommendations for future research proposed.

8.2 Addressing the research questions

The ECB had been collecting injury data as part of their injury surveillance programme from 2010 but had not conducted any collective analysis to fully understand the current injury situation as outlined in phase one of the Team-Sport Injury Prevention Cycle (O'Brien et al., 2019). This led to the formation of the first research question:

i. **What is the injury profile of men's domestic county cricket and how does this differ between game formats?**

Key findings:

- Average match incidence was 102 injuries per 1,000 days of play with highest incidence in One-Day (254 injuries/1,000 days of play), followed by T20 (136 injuries/1,000 days of play) and First-Class 4-Day cricket (68 injuries/1,000 days of play).
- Most match injuries were sustained whilst bowling (41.6 injuries/1,000 days of play), followed by fielding (26.8 injuries/1,000 days of play) and batting (22.3 injuries/1,000 days of play).
- The thigh was the body area most commonly injured (7.4 injuries/100 players per season).
- Lumbar spine injuries were the most prevalent injury with 1.3% of players unavailable on any given day during the season from these injuries.
- A unique injury profile emerged for the shortest format of the game (T20), with increased shoulder injuries relative to other body regions injured compared to other match formats.

- On average, 7.5% of players were unavailable on any given day during the domestic season when all injuries were considered (match and training).
- Match injury incidence was relatively consistent for all competitions, across the nine seasons.

This study was the largest formal analysis of men's domestic cricket injuries in England and Wales to date and provided a robust empirical base for the extent of the injury problem in men's senior domestic cricket in this setting. The findings highlighted the consistency of injury rates across the game and provided a useful baseline for future prevention initiatives to be evaluated against. Yet, for any injury prevention initiative to be effectively implemented, there needs to be 'buy-in' from key stakeholders at the club. Directors of Cricket and Coaches are two key stakeholders who are crucial for the development and implementation of effective preventative initiatives, not least in assigning resource to monitoring/preventive efforts based on their perceived importance. Providing evidence of an association between injury measures and team success may be useful when attempting to communicate the importance of injury prevention to First-Class County Cricket (FCCC) club stakeholders and this need formed the second research question:

ii. Is there an association between injuries and team success in domestic county cricket?

Key findings:

- Moderate reductions in injury burden were associated with potentially worthwhile effects on performance for a men's senior domestic cricket team in the County Championship Division 1.
- A reduction in match injury incidence of 2 match time-loss injuries per 1,000 days of play (90% CI 1.4 to 2.9, P = 0.10) within a team, or a reduction in match injury burden of 75 days per 1,000 days of play (90% CI 50 to 109, P = 0.053) in any given season was associated with the smallest worthwhile change in County Championship points (+13 points) for Division 1, but not for Division 2.

This study was the first to highlight the moderate link between injuries and team success in cricket. These findings need to be understood by stakeholders at clubs and help emphasise the importance of injury prevention efforts. The association was only found when teams were in Division 1, perhaps reflecting the different competitive standard between the two divisions. Injury burden accounts for frequency and severity of injuries. It must be noted that while a practical example was provided on the exact way a team could reduce injury burden (by reducing their total time-loss match injuries by two injuries per season alongside a four-day reduction in severity of all injuries), this was only relevant to the data contained in the study. Thus, causality cannot be directly inferred, and this example is not applicable to future seasons. However, the general finding that reducing injuries can have a positive impact on success is an important one. Better understanding of current practitioner perceptions of injury risk and player monitoring practices would be worthwhile to help explore how such reductions could be achieved. Accordingly, the third research question was developed:

iii. What are the current perceived injury risk factors and player monitoring practices of practitioners in men's domestic county cricket?

Key findings:

- Previous injury and physical fitness were perceived to be the most important intrinsic injury risk factors.
- Reduced recovery time and congested match schedules were perceived to be the most important extrinsic risk factors.
- Monitoring bowling overs was viewed as the most important tool for continually assessing injury risk.
- Player adherence was perceived to be the primary barrier to effective player monitoring, along with human resource and practical application of monitoring knowledge.
- Communicating the value of player monitoring, fostering effective working relationships and strong club culture were important for successfully implementing monitoring and prevention initiatives in this setting.

This study benefitted from a mixed method design as the survey was able to identify and quantify injury risk factor perceptions and prevention practices. The interviews were then able to explore in more detail current practice and perceptions of player monitoring, which is an important tool for injury prevention. But the findings highlighted that before any injury prevention initiatives were considered and implemented in line with the third and final phase of O'Brien et al.'s (2019) Team-Sport Injury Prevention Cycle, more needs to be done to support practitioners in this context with appropriate player monitoring methods and analysis.

While these questions were focussed on the men's domestic game, the extent of the injury situation also needed to be established in the women's game, which at the time had an emerging organisational structure with the game became increasingly more professional. There was also limited research in women's cricket and the injury situation in the women's international development pathway had never been understood, which consequently this led to the fourth research question:

iv. What is the injury and illness epidemiology of the women's international pathway cricket and what influences player availability?

Key findings:

- 8.4% of players were impacted by injury or illness during a typical year, with an average 2.3% of players unavailable on any given day.
- Most medical complaints occurred during training (111.2 injuries/100 players per year).
- Medical illness had the highest overall incidence (45.0 complaints/100 players), followed by hand injuries (24.7 injuries/100 players).
- Overall average match time-loss compliant prevalence was 4.1% and average match time-loss injury incidence was 7.0 injuries/1,000 days of play.
- Fielding (56.4 injuries/100 players per year) was the activity resulting in the highest average overall and time-loss injury incidence rates, though activities labelled as 'other' (e.g. those occurring outside of cricket participation) accounted for 78.3 injuries/100 players per year.

The findings established the current injury situation for women's international pathway cricket, with the high incidence of medical illness relative to other complaints being a potentially distinct feature of the pathway compared to other cricket samples. The part-time nature of players on the pathway presents a challenge for practitioners in this context, with the high occurrence of injuries arising from 'other' activities presenting an opportunity for targeted injury prevention strategies. The lack of understanding of other injury risk factors and mechanisms for this unique population led to the formation of the fifth research question:

v. What are the injury risk factors in women's international development cricket pathway?

Key findings:

- A smoothed 7-day differential load measure had a polynomial relationship with injury risk and is a valid predictive tool for monitoring total player load.
- Session duration and subjective rating perceived exertion was a better predictor of injury than bowling overs.
- Average broad jump scores and 30 m speed also significantly contributed to the best overall performing model, although their effect was smaller than the measure of differential load (that was also included in the model).
- Supervised learning techniques had poor predictive performance when predicting injury but identified important factors associated with injury.

The application of algorithmic models was explored in this study and were able to identify which factors were important and their association with injury risk. The outcomes should have practical relevance to practitioners working in this context and the next stage of this research is to validate these factors and better understand their exact association with injury risk. The finding that a measure of total load involving session duration and a subjective session rating of perceived exertion (sRPE) was a better predictor of injury than the number of overs bowled should have value to practitioners in other cricket playing populations. However, the extent to which the findings are specific to the sample and not generalisable to other cricket samples also needs to be ascertained. This was the first study to explore how algorithmic models may be applied to identify injury risk factors in cricket and while it has provided practical insights for practitioners, it may also provide a framework for such approaches to be applied in other cricket contexts.

8.3 Original contribution to knowledge

This thesis makes an original and significant contribution to knowledge by:

- Formally establishing the injury situation in senior men’s domestic cricket and women’s international pathway cricket, for the first time in England and Wales.
- Finding a potentially unique injury profile associated with men’s domestic T20 cricket, which is the shortest format of the game, with increased shoulder injuries relative to other body regions injured, compared to other match formats.
- Highlighting the negative moderate association between injuries and team success in elite domestic cricket.
- Providing the first investigation into practitioner’s current perception of injury risk and player monitoring practices in elite domestic cricket, highlighting potential barriers and facilitators to injury prevention initiatives.
- Identifying that practitioners working in domestic men’s county cricket require additional support to improve theoretical understanding of player monitoring and its practical application.
- Demonstrating that communicating value, fostering effective working relationships, and a strong club culture are important for successfully implementing monitoring and prevention initiatives.
- Validating the use of a 7-day smoothed differential total load for effective player monitoring to manage injury risk.
- Exploring how algorithmic models may be applied to identify important injury risk factors, and their association with injury, providing practical insights for practitioners in that setting.

8.4 Discussion of methodological approach

In line with Hernán et al's (2019) categorisation of data analytics, Chapters three, five and six used descriptive analytical techniques, with chapter four and seven using predictive methods, which map inputs (factors) to outputs (predictions). The injury data used throughout this thesis was collected as part of the England and Wales Cricket Board Injury Surveillance Programme. A strength of this data lies in the size of the dataset and the consistent methodology with which it has been collected since 2010 for the men's domestic game and since 2015 in the women's international pathway. Data for the women's international pathway has the added strength of being collected from the onset of the pathway, as the sport was becoming increasingly more professional. With fewer squads to manage, the consistency of the methodology was more closely managed, which has resulted in a 'richer', more complete dataset that allowed for more complex statistical approaches to be employed with confidence in Chapter seven.

Even though the men's domestic cricket injury surveillance data was collected over a longer time period, with 18 different clubs inputting data into a centralised system, there is a greater chance of error and less confidence a consistent methodology has been followed. Furthermore, in 2017 the ECB moved from one purpose-built central online medical records system called Profiler (The Profiler Corporation, New Zealand), to another called Cricket Squad (The Sports Office, UK). Although both systems are similar in their capability and functionality, any change in process can increase the potential for error as practitioners get used to working with a new system. There is increased risk of differential misclassification as practitioners vary in their ability to adapt to a new system. The ECB tried to somewhat mitigate this risk by providing initial training and continued support to all physiotherapists, but the risk of random error resulting from the transition and learning a new system still needs to be considered, which would be most notable for 2017 season data, when the new system was implemented.

Outside of ECB's internal processes for injury surveillance data collection, the international consensus statement on injury surveillance in cricket originally published in 2005 (Orchard et al., 2005) was updated in 2016, halfway through the data collection period. The updated consensus contained (among other things) updated definitions for non-time loss injuries, which were excluded from the original consensus. While the original 'significant' cricket injury definition was retained and renamed specifically to 'match time-loss' (for when injuries cause the player to be unavailable on scheduled match days) and 'general time-loss' (refers to any day a player is unavailable for selection regardless of whether there is a match or not). Another injury definition was provided for injury surveillance at the elite level: 'medical attention' injuries. This term relates to any health-related condition that required medical attention with the potential to affect cricket training or play and included time-loss and non-time-loss injuries. These updated definitions may have impacted the way practitioners classify injuries and could have again jeopardised the level of consistency in the data collection methodology following the publication of the updated consensus in 2016. That said, the consistent levels of time-loss injuries described in Chapter three, may demonstrate the minimal impact these changes have had on injury incidence rates, which reflects the lack of disruption to data collection. The impact of any changes would have been evident in substantial variation from the baseline (for the year of any changes), which would have been identified through the Statistical Process Control charts used in Chapter three and highlights some of the value added by the charts when applied in this context.

The updated definitions may not have impacted the injury incidence rates demonstrated in Chapter three, as Chapter three focused just on 'significant' cricket injuries whose definition did not really change in the updated consensus, but was just separated into 'match' and 'general' time-loss injuries. The definition remained relatively unambiguous:

> 'Any injury or other medical condition that either: (1) prevents a player from being fully available for selection for a major match *or* (2) during a major match, causes a player to be unable to bat, bowl or keep wicket when required by the either the rules or the team's captain.' (Orchard et al., 2016 p. 1246).

However, for other injuries there is still some ambiguity around their classification as either a time loss or non-time loss injury. For instance, if a player usually both bats and bowls during a game, but sustains an injury that results in them unavailable for selection to bowl, should this be considered a non-time loss injury if they are still available for selection to bat? Or is this a time-loss injury as they are not available for selection for their full range of usual duties? On this point the updated consensus concedes "these determinations may need to be made on a case-by-case basis" (Orchard et al., 2016 p. 1250). This reflects the ambiguity around this and the scope for subjective interpretation that may differ between practitioners, increasing the risk of differential misclassification bias between clubs. This element of a player undertaking different roles depending on the phase of the game, is a unique aspect of cricket compared to other team sports. Practitioners in this context would benefit from further clarification and guidance on this, which the ECB are keen to set, to ensure consistent methodology for injury surveillance data collection and classification is maintained. The extent to which this potential bias may have affected the validity of the results has been considered but not deemed to be significant. Improvements can always be made, and while there may be differential misclassification bias between clubs, this risk was somewhat reduced and its impact diluted when the data was aggregated across the domestic county game. This was demonstrated by the consistency of injury rates over nine seasons, as illustrated by the Statistical Process Control (SPC) charts in Chapter three.

The use of Statistical Process Control (SPC) in Chapter three was the first time such charts have been used in cricket injury research and effectively visualised the consistent injury rates and provided a useful tool for future monitoring. A strength of the approach is the ability to detect statistically significant changes over time, but it is somewhat limited by the amount of time and data required to identify any special variation from a particular data point's own historic baseline. There is also the consideration to the lack of validation in using SPC charts in this context. There might be a thresholding effect and such thresholds may not be optimised to fully detect meaningful changes in match injury incidence. Nevertheless, it still may provide a method for continuing to evaluate the effectiveness of injury prevention initiatives that has been found to be practically worthwhile in other disciplines (such as health [Mohammed et al., 2001; Benneyan et al., 2017], biology [Bramwell, 2013] and the military [Scholl et al., 2017]).

Chapter four saw the use of magnitude-based inferences as a complimentary analysis to a linear mixed model that explored the association between with-in team injury measures and performance. Magnitude-based inferences (MBI) were developed to address the drawbacks to the dominant frequentist approach within exercise science and epidemiology, that is Null Hypothesis Significance Testing (NHST). Results using NHST are deemed 'statistically significant' if the associated *P*-value (that represents the likelihood of obtaining an effect larger than the one observed, if the null hypothesis were true) is less than a threshold value that is typically set as 0.05. But NHST is sensitive to sample sizes, where trivially small effects can be found to be significant with large sample sizes even if they are not practically important (e.g., Type I error). Conversely if a study is too small, there may be an effect, but it is deemed to be non-significant (e.g., Type II error) as the analysis is underpowered. MBIs provide the ability to evaluate and interpret effects in terms of practical relevance and can be qualified with a probabilistic qualitative term to provide more informative inferential assertions about the magnitude of the effect (beneficial, trivial, or harmful). However, the use and suitability of MBIs has become a much-debated topic in sport science (Impellizzeri et al., 2019) with criticism including (but not limited to); the approach potentially underestimating sample size needs (Welsh & Knight, 2015), inappropriate control of Type I error rates (Sainani, 2018) and authors drawing 'overly optimistic' conclusions from their data (Lohse et al., 2020). That said, no statistical approach is perfect, and the goal of MBIs to move researchers past the fallacies of NHST is worthwhile and delivers value as a complimentary analysis that also provides a qualitative way to comment on the relevance of the magnitude of the effects that is easily interpretable. Whatever approach is used, always reporting confidence intervals and effect sizes with any analysis should allow other researchers and practitioners to evaluate and interpret the effects as well as their practical relevance.

The benefits of the additional context afforded by supplementary methods was demonstrated in the mixed methods study design employed in Chapter five. Such is the nature of mixed methods research the complementary strengths of both quantitative and qualitative approaches can provide greater insights when both results are collectively considered. But this can be a bit of a double-edged sword, as while there are strengths of both approaches, double the methods, bring with them double the potential limitations to consider as alluded to in Chapter five. As noted previously, where there is real value in different statistical approaches and complementary analysis, the same is true with mixed methods design. The additional context afforded by the qualitative methods provided valuable insight that would not have been garnered from quantitative methods alone and greatly enhanced the findings of the overall study. For example, the quantitative survey highlighted what injury risk factors were perceived to be important by practitioners. The qualitative interviews then highlighted the transitioning culture of cricket that presents a challenge and potential barrier for the effective implementation of any potential preventative strategies in this area, with science and medicine approaches not being fully embraced by all players and coaches in the domestic game. What's more, the ability to triangulate qualitative and quantitative findings allows for researchers to check for consistency in responses across both methods (Creswell, 2003), noting areas of convergence within the findings that strengthen the knowledge claims of the study (McKay et al., 2020).

With statistical approaches, it is about selecting the right 'tool' for the right 'job' and in the final chapter, the use of algorithmic models was explored. The dynamic and complex nature of injuries requires more complex statistical approaches to fully capture their dynamic and multiplex nature (Ruddy et al., 2019), but it could be argued the exact role of such approaches in sports injury research is still being determined. The value of such approaches might not be in the more conventional application of predicting injuries (where these approaches have typically performed poorly) but as a useful way to explore and extract the most important factors. The potential multiple interactions of these factors and their association with injury can then be explored with more conventional statistical data models. This does not mean reductionist statistical approaches are less relevant in this field. As Ruddy et al. (2019) suggested, reductionist statistical approaches are a valid and useful method for informing and implementing algorithmic models as well as studying any important factors in isolation. With most statistical approaches, as outlined previously, it is about what tool helps address the research question in hand. Just because technology has afforded the application of complex approaches, does not always necessarily mean one should.

The use of supervised learning techniques is not without its challenges. With multiple testing (as was the case in Chapter seven where multiple outcomes are being analysed at once), there is the risk of potentially inflating the type I error rate (Li et al., 2017). This is particularly pertinent when the model is being used to identify new factors. While the model was able to identify important risk factors, these may only be relevant for the context the sample was derived from and as such, prospective validation of the model is essential to increase confidence in the importance of these factors. It may be that the risk factors are specific to players on the international women's pathway. There is no issue with this, and a worthy finding for practitioners in this context if it were the case. But even still, prospective validation is needed even for this specific use case to strengthen the credibility of the findings. The additional consideration with this, is the amount of data required for such techniques to be meaningful and the challenge for further validating the model in additional cohorts. As an example, even though data used in Chapter seven was collected over a reasonable time period, it still only included a small number of players with a small number of injuries that increases the potential for model outfitting.

Algorithmic models such as supervised learning techniques are popular in a variety of disciplines but should not be employed for the sake of it. While such approaches should certainly be explored, sport science (particularly in cricket) needs to ensure it is doing the fundamentals well first. The findings from the studies that make up this thesis would suggest such advances in technology and gains made in computer processing that enable the application of such complex approaches, would be better initially served ensuring any statistical methods employed are done so on an individual level. Traditional statistical methods sought to test a sample so that the findings could be generalised to the wider population as not everyone in the population could participate in the study. Now though, technology enables mass data collection and processing and so this should be harnessed to make inferences on an individual level, which within sport, is made even more possible by a reduced 'population' of interest. This is not to say there is no longer the need for generalisability in research findings, just that individual data collection and inferences would result in more robust data available for complex approaches to identify more specific, relevant and dynamic generalisations across 'samples' or 'populations' that may not have previously been known or possible.

As a researcher, it is best to be open-minded and well-versed with a variety of different methodological approaches and knowing which ones will enable you to best address the research question. It is important to acknowledge each approach has their own strengths and weaknesses and doing what you can when designing the study to overcome any potential limitations, as well as considering any potential complimentary analysis that may help better answer the question, or at least certain aspects of it.

8.5 Practical implications and potential impact

The aim of this programme of work was to produce research that would aid understanding of the current injury situation in men's domestic and women's international pathway cricket, inform practice and describe what injury risk factors and mechanisms may guide future prevention strategies. Outlining the practical implications resulting from this thesis is crucial to fulfil this aim. The knowledge produced by this thesis is likely to be of most interest to medical/strength and conditioning staff as well as those focused on improving performance: coaches, Directors of Cricket, and club CEOs. The potential impact of this work on ultimately reducing injury burden can be continuously monitored through the ongoing ECB Injury Surveillance Programme.

The Statistical Process Control (SPC) charts used in Chapter three provide a practical tool for continually monitoring the impact of any efforts on reducing injury burden. The results from that chapter established the current injury situation in this sport for practitioners, with the SPC charts illustrating the consistency of these injury rates over the nine seasons of data. Furthermore, the consistently high injury rates for certain body regions, that enforce findings from previous international research (Frost & Chalmers, 2014; Orchard et al., 2016), should guide focus for practitioners and future researchers in this area, highlighting the potential priority areas for injury prevention strategies, most notably lumbar spine and thigh injuries. As a result of these findings, a working group of ECB and (a selection of) county science and medicine staff has been formed to collectively develop understanding and strategies to reduce thigh injury incidence and burden.

The association between injury and team success demonstrated in Chapter four should be more relevant for coaches, club CEO's and Directors of Cricket and emphasise the importance of injury prevention initiatives and the adequate resources required by science and medicine staff at county clubs to prevent injuries. This message seems particularly pertinent given the practical insights provided by Chapter five that identified the perceived importance of player monitoring by key stakeholders at the club and effective working relationships are crucial for successfully implementing injury prevention initiatives.

The results from Chapter five should also have implications for the ECB, with the finding that practitioners within the domestic county game would benefit from further support on player monitoring methods and analysis. The potential impact of further support from the ECB would be enhanced theoretical understanding on player monitoring for practitioners and practical knowledge that in turn, will benefit the ECB in ensuring the reliability of future load data collection (an important injury risk factor) and buy-in for potential prevention initiatives. Additionally, another consideration for the ECB is the suggested barrier for science and medicine within some domestic county clubs, and the transitioning culture of the sport. Although there are some keen science and medicine practices happening within clubs, it appears this can sometimes be disconnected from senior management and coaches. This insight should also prompt reflection by club science and medicine practitioners on their current working relationships and practices with key stakeholders at their clubs and how this may be improved.

The results from Chapter six and seven should have much needed practical implications for practitioners working with the women's international pathway where previous research has been scarce, as this aspect of the game becomes increasingly more professional. Furthermore, the findings will add to the growing empirical base for this sport that will benefit those involved in women's cricket internationally. Like Chapter three for the men's domestic game, Chapter six establishes the extent of the current injury situation whilst also highlighting to those outside of the international pathway, the unique challenges faced by those working in this context. This may have the potential impact of more support from the ECB (or domestic clubs when the new domestic structure is introduced) for practitioners in this setting to help overcome or better manage these challenges. The findings also provide practical guidance on potential injury prevention opportunities (notably medical illness, injuries resulting from fielding and activities labelled as 'other') for international pathway practitioners that may undoubtedly have positive impact for all involved.

Chapter seven identified injury risk factors that may be useful in player screening to identify players at increased risk of injury. What is more, further validation for the smoothed 7-day differential load measure (Tysoe et al., 2020) as a viable alternative to the often used ACWR (as demonstrated in Chapter five) has practical relevance for practitioners in the men's domestic county cricket game and in other cricket playing populations. Monitoring bowling workloads is recognised as important for managing injury risk and widely practiced across the game (Chapter five; Dennis et al., 2005; Orchard et al., 2009; Orchard et al., 2015). But the findings from Chapter seven, suggest that it may be just as worthwhile to monitor workload by session duration and a subjective sRPE score (it was found in Chapter seven to have greater predictive power in compared to an exponentially-weighted moving average 7-day measure of just bowling overs). The sRPE has the benefit of providing a simple and practical way to accommodate and measure individual variation in load response (Chapter seven; Warren et al., 2018).

The ability to apply the statistical techniques used in Chapter seven to provide information on the most appropriate measures to assess injury risk, should have practical benefits for both practitioners and players, by reducing the number of measures collected for testing and monitoring purposes. Such algorithmic models may also identify important factors that may otherwise not been apparent. The methodology deployed and results from this thesis may provide a practical framework for those in other sporting or cricket populations to adopt and spur future research.

8.6 Future research

The research questions proposed in this thesis have been addressed for the first time in an elite domestic men's cricket and women's international pathway population. This process has been guided by the three phase Team-Sport Injury Prevention Cycle (O'Brien et al., 2019). The first phase of understanding the current injury situation guided chapter three and six. Chapters four, five and seven were guided by the second phase, of identifying injury risk factors (chapter seven) that can inform injury prevention strategies and understanding any potential facilitators and barriers (chapter four and five) to the effective implementation of future injury prevention initiatives to reduce the injury burden. This section outlines potential future studies that can build upon the knowledge gained from the investigations contained within this thesis.

Future research can look to continue working through the Team-Sport Injury Prevention Cycle by exploring potential injury risk factors and mechanisms in the second phase, but also into the third and final phase of implementing and evaluating injury prevention initiatives. The consistency of the injury rates found in the men's domestic cricket game presented in chapter three establishes a baseline for future prevention measures to be evaluated against and a useful tool for further monitoring. But reducing injury burden is not going to be without its challenges. Establishing the consistency of injury rates is the first step towards what would need to be a concerted effort across the domestic game, to try and prevent injuries and reduce injury rates in the future. Such efforts will require a collective discipline and a systematic approach, like what the Team-Sport Injury Prevention Cycle has provided for this thesis.

Based on the findings of Chapter three, future research might want to initially focus on lumbar spine and thigh injuries, given the consistently high injury incidence of these over the nine seasons contained within the study period. Exploring the Orchard codes, activity at time of injury and month of injury in more detail might identify risk factors and mechanisms that can be targeted for future prevention initiatives. If this proves fruitful, it could provide a framework for continuing to work through the other body regions injured ranked by mean incidence presented in Chapter three, starting with the highest to the lowest. Furthermore, the potential unique injury profile identified in men's domestic T20 cricket, with increased shoulder injuries relative to other body regions injured in other match formats, also warrants further investigation.

The valuable insight into practitioner perspectives of injury risk and current load monitoring practices gained from the findings in Chapter five will help inform potential barriers and facilitators to implementing any injury prevention initiatives. It would also be worthwhile for future research to gain the perspective of coaches and Directors of Cricket in relation to injury surveillance and prevention strategies. This programme of work has been focused and led by science and medicine staff, but it is important to gather insight from all key stakeholders with a vested interest in reducing injury burden.

Qualitative investigations such as the one that formed part of the methodology in Chapter five should continue to be used (either as a compliment or standalone methodology) in future research, which would benefit from the additional context and value such methods provide (Bekker et al., 2020). One area that might benefit from a follow-up qualitative investigation is to gain the perspective of practitioners to evaluate any additional support that may be provided by the ECB to enhance theoretical understanding of player monitoring and its practical application. This would serve to follow up a practical implication that emerged from the findings in Chapter five. The combined knowledge generated from using mixed methods where possible, can maximise the chances of future research being translated into injury prevention practice (Finch, 2006).

In a similar way to how it was outlined future research can build from the foundations laid by establishing the extent of the current injury situation in the men’s domestic, the same is true for Chapter six and the women’s international pathway. The finding of high medical illness and injuries resulting from activities classified as ‘other’, which are often from non-cricket playing activities due to the part-time nature of players on the pathway, presents a targeted injury prevention opportunity for future research and practitioners in this context. Also, the high incidence of fielding injuries, which is consistent with previous research in women’s cricket (Warren et al., 2019; Perrea et al., 2019), requires further investigation to ascertain the specific risk factors and mechanisms for these types of injuries. The upcoming incorporation of a more professional domestic structure presents considerable opportunity for future research. The new structure will bring with it new injury profiles to consider for that setting and the extent of the injury situation will need to be established specifically for that context, starting over with the first phase of the Team-Sport Injury Prevention Cycle (O’Brien et al., 2019). The consistent structure will enable future research to continue to move through the cycle and a real opportunity to identify injury risk factors and mechanisms, as well as implement and evaluate any injury prevention initiatives. The advantage of incorporating a new domestic structure is the ability to plan injury surveillance and the injury prevention cycle into practitioner practice, allowing these processes can grow with the sport.

Finally, Chapter seven identified potentially important injury risk factors that would certainly benefit from future research following up to validate these factors and determine their exact association with injury. Average broad jump scores and speed over 30 m were the only physical profiling measures to contribute to the best-fit model for predicting injury. However, their effect on injury risk was small and it may be specific to the sample, which also needs determining in future research. With any scientific endeavour, future research needs to reproduce these findings to ascertain their reliability and trustworthiness. This could be done with a different sample in the same population, a sample that shares similar characteristics, or other cricket-playing populations to explore how generalisable these findings are. Due to nature of the supervised learning techniques deployed, it is suggested each population should identify their own important injury risk factors that are specific to their setting. Chapter seven provides a methodology for exploring how both algorithmic and conventional data models could be applied in other cricket samples. It is hoped future research will continue with this, firstly with data from the ECB men's domestic and/or international games.

One finding that does seem universal to any cricket playing populations is the need to monitor players and base decisions on individualised data. Though this is not just in relation to load monitoring, future research should also explore whether important injury risk factors can be identified by algorithmic models on an individual player level. It may be that average broad jump score is an important injury risk factor for one player, but total shoulder range of motion is a better predictor for another player who is more susceptible to shoulder injuries. The individual variation suggested in Chapter seven and demonstrated in previous research (Warren et al., 2018), suggests this could be worthwhile. Future research should explore and evaluate not just establishing mean individual baseloads for continual load monitoring, but also what factors are the best predictors of injury, specifically for each player in each context. The methodology used in Chapter seven could provide a framework for this exploration and such approaches would then serve to decrease unnecessary testing and allow practitioners to work closer with athletes and focus on developing areas where they are most at risk of injury.

For this to be fully effective, it is worth considering greater collaboration with other researchers. A challenge with any sports injury research, is the large sample size required to yield meaningful inferences. This is particularly pertinent when we are applying algorithmic models in this context. As such, future research in this area might benefit from pooling resources, to increase the size and quality of the data collected, which can be analysed for more robust findings. One such initiative is the Open Science Framework that aims to make it easier to create, share and develop projects, to foster greater collaboration between researchers (Foster & Deardorff, 2017).

Finally, any future research that aims to develop risk prediction models should ensure they report an assessment of operator variability to add trustworthiness to the data reported and follow the Transparent Reporting of a multivariable prediction model for Individual Prognosis or Diagnosis (TRIPOD) guidelines (Moons et al., 2015). These recommendations serve to raise the quality of risk prediction model research, ensuring the usefulness of any prediction models studies can be adequately understood, assessed, and replicated.

8.7 Thesis conclusion

The aim of this thesis has been to understand the injury profile of the men's domestic county game and women's international pathway in England and Wales, to inform future prevention strategies. To fulfil this aim, five novel research questions were addressed using longitudinal injury data collected as part of the ECB Injury Surveillance Programme.

This programme of work has confirmed the importance of injury prevention efforts and communicates their value to all key stakeholders within the ECB and domestic county clubs. The knowledge gained from these investigations should also highlight the need for continued consistent data collection, support for practitioners to aid their understanding and effective application of player monitoring practices and appropriate analysis strategies for the dynamic and complex nature of sport injury data. The association of reduced injury burden with team success has been demonstrated for the first time in elite domestic men's cricket. Consistent injury incidence rates provide a baseline from which future prevention initiatives can be evaluated against. Lumbar spine and thigh injuries were found to be particularly pertinent for the men's domestic game, with medical illness and injuries sustained from 'other' activities presenting an opportunity for injury prevention on the women's international pathway. Communicating the value of injury prevention efforts, fostering effective working relationships, and a strong club culture were important for successfully implementing monitoring and prevention initiatives. A way of monitoring player load involving session duration and sRPE has been proposed as a viable alternative to just monitoring bowling overs, with broad jump average scores and 30 m speed scores important factors in predicting injury in a sample of players from the women's international pathway. The use of algorithmic models to identify important injury risk factors were explored but, consistent with previous research performed poorly in relation to predicting injury. That said, such techniques demonstrated potential for identifying important injury risk factors and should be applied in other cricket playing populations. These techniques could also be used to identify important injury risk factors on an individual player level that can guide practice and enhance the support provided and received by science and medicine staff and players, respectively.

The results from this thesis contributes to our understanding of injury risk in elite domestic men's and women's international pathway cricket and have important implications for future injury prevention practice and research.

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APPENDICES

APPENDIX A: ECB Injury Surveillance Consent Form (Chapters 3,4, 6 and 7)

ECB Injury Surveillance Programme

The England and Wales Cricket Board's (ECB) Injury Surveillance Programme (ECB IS Programme) seeks to collate and analyse injury and illness data (Injury Data). This will assist the ECB in determining the rates and severity of, as well as potential risk factors for, the most common injuries suffered by cricketers.

The ultimate aim of the ECB IS Programme is to gather insight of injury trends and to implement measures in order to help reduce injury occurrence amongst cricketers.

The ECB works with a sports injury research partner (currently University of Bath) who will assist in the analysis of Injury Data and prepare pooled and anonymised data for publication, and to help the ECB achieve the ECB IS Programme objectives.

Consent

Please read and tick the relevant box below to confirm whether you agree to participate in the ECB IS Programme and sign in the place provided at the end of this form.

ECB IS Programme	Tick as appropriate	
	Yes	No
I consent to take part in the ECB IS Programme and to my name and Injury Data that is held by the ECB being provided to the ECB's sports injury research partner in order for them to provide analysis and research based on this data and to publish their pooled and anonymous findings.		
	IF YOU TICK 'NO', A DESIGNATED MEDICAL PRACTITIONER AT THE ECB MAY CONTACT YOU TO DISCUSS YOUR DECISION WITH YOU	

Your rights: You are entitled to a copy of your personal data from the ECB (a small fee may be payable) and to correct any inaccuracies in it.

Signature: Name:

Date:

APPENDIX B: COREQ (Consolidated criteria for Reporting Qualitative research) checklist (Chapter 5)

Developed from: Tong A, Sainsbury P, Craig J. Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups. *Int J Qual Health C*. 2007;19:349:357.

Topic	Item No.	Guide questions/description	Reported on Page No.
Domain 1: Research team and reflexivity			
Personal Characteristics			
Interviewer/facilitator	1	Which author/s conducted the interview or focus group?	81
Credentials	2	What were the researcher's credentials? E.g. PhD, MD	81
Occupation	3	What was their occupation at the time of the study?	81
Gender	4	Was the researcher male or female?	81
Experience and training	5	What experience or training did the researcher have?	81
Relationship with participants			
Relationship established	6	Was a relationship established prior to study commencement?	81
Participant knowledge of the interviewer	7	What did the participants know about the researcher? e.g. personal goals, reasons for doing the research	81
Interviewer characteristics	8	What characteristics were reported about the inter viewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic	81
Domain 2: study design			
Theoretical framework			
Methodological orientation and Theory	9	What methodological orientation was stated to underpin the study? e.g. grounded theory, discourse analysis, ethnography, phenomenology, content analysis	80, 82
Participant selection			
Sampling	10	How were participants selected? e.g. purposive, convenience, consecutive, snowball	81
Method of approach	11	How were participants approached? e.g. face-to-face, telephone, mail, email	81
Sample size	12	How many participants were in the study?	81
Non-participation	13	How many people refused to participate or dropped out? Reasons?	81

Setting			
Setting of data collection	14	Where was the data collected? e.g. home, clinic, workplace	81
Presence of non-participants	15	Was anyone else present besides the participants and researchers?	81
Description of sample	16	What are the important characteristics of the sample? e.g. demographic data, date	81
Data collection			
Interview guide	17	Were questions, prompts, guides provided by the authors? Was it pilot tested?	81, Appendix D
Repeat interviews	18	Were repeat inter views carried out? If yes, how many?	81
Audio/visual recording	19	Did the research use audio or visual recording to collect the data?	81
Notes	20	Were field notes made during and/or after the interview or focus group?	81
Duration	21	What was the duration of the inter views or focus group?	81
Data saturation	22	Was data saturation discussed?	N/A
Transcripts returned	23	Were transcripts returned to participants for comment and/or correction?	83
Domain 3: analysis and findings			
Data analysis			
Number of data coders	24	How many data coders coded the data?	82
Description of the coding tree	25	Did authors provide a description of the coding tree?	N/A
Derivation of themes	26	Were themes identified in advance or derived from the data?	82
Software	27	What software, if applicable, was used to manage the data?	81
Participant checking	28	Did participants provide feedback on the findings?	83
Reporting			
Quotations presented	29	Were participant quotations presented to illustrate the themes/findings? Was each quotation identified? e.g. participant number	Appendix E
Data and findings consistent	30	Was there consistency between the data presented and the findings?	86-90, Appendix E
Clarity of major themes	31	Were major themes clearly presented in the findings?	86
Clarity of minor themes	32	Is there a description of diverse cases or discussion of minor themes?	86-90

APPENDIX C: Workload and player monitoring questionnaire (Chapter 5)

Page 1: Introduction and consent

This questionnaire includes 12 questions (10 closed and 2 open) and should take approximately 15 minutes to complete. The questionnaire aims to establish current perceptions and practices of workload and player monitoring as part of pre-season preparations in elite men's domestic cricket. It is broken down into three sections, the first asks for your opinions regarding injury risk factors in cricket. The second section will focus on your practices for testing and monitoring injury risk in your players with the final section exploring your perceptions of workload and player monitoring specifically.

Please take your time and read through each question carefully before responding as requested. Four of the ten closed questions require you to select how important a given factor is to you (from 'very important' to 'not important' as well as an option for 'not sure'). Two of the ten closed questions ask you to state how often (if at all) you used a particular test/tool (given in a list) and whether this was just pre-season or continuously through the pre and in-season. All responses are anonymous and confidential, so please answer honestly.

1. After reading the information provided in relation to this study, please select one of the following before completing the questionnaire:

a) I consent to participate
b) I do not consent to participate

2. Please enter your personal 'Club ID' that has been provided to you for the purpose of this questionnaire:

Club ID:

Please select your role at your club:

a) Physiotherapist
b) Strength & Conditioning Coach

Page 2: Testing and monitoring practices

This section will focus on your practices for testing and monitoring injury risk in your players

1. Did you assess 'individual players' injury risk profile last season (2018)?
    a. During pre-season only
    b. Continuous assessment throughout pre and in-season
    c. Did not assess individual injury risk profile

2. If yes, did you provide specific training modifications to coaching staff for players identified with high risk for injuries?
    a. Yes
    b. No

3. If yes, please can you provide an example of the type of modifications suggested:

4. Please specify how often you implemented (if at all) the following tests to *identify* injury risk in your players last season (2018).

Please do not select more than 1 answer(s) per row.

*Response – *'Did not implement'/ 'During pre-season only'/'Continuous assessment throughout pre and in-season'*/ for each of the following:

a) Functional Movement Screen (FMS)

b) In-house adapted Functional Movement Screen

c) Evaluation of muscle peak strength

d) Evaluation of muscle endurance strength

e) Evaluation of muscle activation / control patterns

f) Evaluation of side to side muscle imbalance

g) Evaluation of agonist:antagonist muscle imbalance

h) Maximal physical fitness test

i) Sub-maximal physical fitness test

j) Balance / proprioception

k) Flexibility

l) Joint mobility / function

m) Psychological evaluation

n) Other (Please state)

5. Please specify how often you employed (if at all) the following tools to *assess* injury risk in your players?

   Please do not select more than 1 answer(s) per row.

   *Response – *'Did not implement'/ 'During pre-season only'/'Continuous assessment throughout pre and in-season'*/ for each of the following:

a) Rating of perceived exertion (RPE)
b) Heart rate (during training)
c) Heart rate variability
d) Subjectively rated fatigue
e) Subjectively rated sleep
f) Subjectively rated muscle soreness
g) Subjectively rated recovery status
h) Objective measure of sleep (e.g. sleep watches)
i) Recovery of muscle force
j) Biochemical markers of blood
k) Biochemical markers of saliva
l) General medical screen
m) Number of matches / minutes played
n) Overs bowled in match
o) Overs bowled in training
p) Deliveries faced in match
q) Deliveries faced in training
r) Distance covered in match
s) Distance covered in training
t) Acute:Chronic Workload Ratio (ACWR)
u) Other (please state)

6. Could you please rate your 5 **most important** monitoring tools that you use to determine injury risk in your players?

    1st

    2nd

    3rd

    4th

    5th

Page 3: Risk Factors

This section is about your opinions regarding risk factors for injury in the cricket players you work with.

7. How important are the following **INTRINSIC** risk factors for injury in your players:

Please do not select more than 1 answer(s) per row.

*5 point Likert scale response: *Very important / Important / Somewhat important / Not important / Not sure* / For each of the following:

a) Previous injury

b) Age

c) Maximal muscle strength

d) Strength endurance (e.g. resistance to fatigue)

e) Muscle imbalance (side to side difference)

f) Muscle imbalance (Agonist:Anatagonist)

g) Acute fatigue (i.e. following intense actions in a match)

h) Accumulated fatigue (i.e. throughout a season/congested match periods)

i) Physical fitness

j) Balance/coordination

k) Flexibility

l) Movement efficiency

m) Sleep

n) Wellness (mood, fatigue, muscle soreness)

o) Psychological factors (e.g. stress, anxiety)

p) Other (please state)

If you selected ‘Other’, please can you provide some additional information and/or examples:

8. How important are the following **EXTRINSIC** risk factors for injury in your players:

Please do not select more than 1 answer(s) per row.

*5 point Likert scale response: *Very important / Important / Somewhat important / Not important / Not sure* / For each of the following:

a) Congested match schedule
b) Reduced recovery time between matches
c) Number of matches/minutes played during the season
d) Training load
e) Training type
f) Footwear
g) Poor surface quality
h) Change in surface type (even if surface quality is good)
i) Climate
j) Frequent travel
k) Quality of training facilities
l) Quality of recovery facilities
m) Importance of matches
n) Internal communications (i.e. between staff)
o) Key staff changes (i.e. consistency of same staff group)
p) Game format
q) Playing position
r) Other (please state)

If you selected ‘Other’, please can you provide some additional information and/or examples.

Page 4: Workload and player monitoring

This section will focus on your perceptions of workload and player monitoring as an injury risk in your players

9. How important is workload and player monitoring for the following?

Please do not select more than 1 answer(s) per row.

*5 point Likert scale response: *Very important / Important / Somewhat important / Not important / Not sure* / For each of the following:

a) Maximising performance
b) Reducing injury risk
c) Competition readiness
d) Player wellbeing
e) Other (Please state)

If you selected ‘Other’, please can you provide some additional information and/or examples.

10. How important are the following on impacting the effectiveness of workload and player monitoring?

Please do not select more than 1 answer(s) per row.

*5 point Likert scale response: *Very important / Important / Somewhat important / Not important / Not sure* / For each of the following:

a) Cost
b) Human resource
c) Support from management
d) Access to hardware
e) Access to software

f) Technical knowledge of how to effectively use hardware
g) Technical knowledge of how to effectively use software
h) Player adherence
i) Theoretical understanding of workload and player monitoring
j) Practical application of workload and player monitoring knowledge
k) Knowledge of effective metrics to use
l) Club philosophy
m) Coach philosophy
n) National Governing Body advice and guidance
o) Other (please state)

If you selected ‘Other’, please can you provide some additional information and/or examples.

11. Is there more you would like to do to monitor players and workload?
    a. Yes
    b. No

12. If yes, can you briefly provide some additional information (or key words) on what you would like to be doing more to monitor players and workload:

Page 5: Finally

We are looking to conduct follow-up focus groups with interested County Clubs to discuss in more detail current practice and perceptions of workload and player monitoring. Participation is entirely voluntary and focus groups will only include sport practitioners involved in workload and player monitoring from the same County Club. The focus group will be arranged at a time most convenient to you and can be held at your County ground. All responses will be anonymous and confidential.

If you are interested in participating and happy to provide consent to be contacted by the lead researcher regarding this follow-up project, please select the appropriate box below.

- Yes, I am happy to be contacted
- No, I would prefer not to be contacted

Thank you again for your time and interest in this study.

If you have any questions or would like to discuss anything related to this study further, please contact the lead researcher via email.

APPENDIX D: Interview guide prompts (Chapter 5)

Main questions and probes

What are you currently doing to monitor players (and workloads)?

How long have players (and workloads) been monitored and what was the reason this was implemented?

What do you use this data for (purpose)?

How is this data practically applied by the Science & Medical department?

How is the use of this data communicated to players?

What is the perception of the role/application of this data at different levels of the club (e.g. players, science & medicine staff, coaches/managers)?

What would you like to do that you are not currently doing in relation to player monitoring?

What is holding you back (if anything)?

What are your current philosophies to pre-season preparations?

What (if anything) informed this philosophy?

Are there any metrics/measures you use?

What do you think other clubs might be doing?

APPENDIX E: Table of quotes (Chapter 5)

Theme (sub-theme)	Quote
Perceived importance of player monitoring	*'No. I think so to be completely honest I think there are some facets of our monitoring that they see the importance of, but there are others they don't see It … I think that's solely down to us though as practitioners and how we sell it' (S&C Coach, 01)* *'I think players are generally on board, there are always individuals who don't bel- there's a couple of individuals out there who don't necessarily believe in bowling workloads in th-in their crudest sense, they would obviously still select when they need to recover and as and when they need to bowl, but they're not going to be that interested in the numbers from me … whereas other bowlers, 'er completely other end of the spectrum and would want to know er would want that information but, a lot of the times from a bowling workload perspective a lot of that information sits in front of the science & medicine team rather than being exposed to the players' (Physio 01)* *'We were trying to get the coaching staff on board as to erm … the importance of workload monitoring and how workload may have a relationship with injury' (Physio 01)* *'cricketers will naturally get injured because it's becoming more of an athletic sport. So, we're very lucky that we've got a crop of players who buy in heavily to the S&C er side of things' (Physio 02)* *'they're (players) they're quite data driven cos they're naturally competitive and they want to be better than the bloke next to them whether they admit that or not, when really they should just be trying to beat themselves' (S&C Coach 02)* *'when you watch the cricket, you know what they're doing but you know when you're looking at training sessions and what not post that game you know whether guys need more overs or whether they don't and weeks where you're resting guys, erm what bowling they need to do that week just to keep things erm, keep things in order with what they've previously done' (S&C Coach 02)* *'(implemented) I think it was just to take any guesswork out of erm, what the players were experiencing through erm, through their cricket through their training erm, and just to be a bit more accurate with training prescriptions, if they, if we know we are trying to scale things up what that actually looks like per individual' (S&C Coach 02)* *'it's part of the job isn't it, if you're it's evidence-based practice what you're be doing as a practitioner, if its if you're guessing it's not really it's not sports science' (S&C Coach 02)* *'I think it's more information as well so you've got an objective measure to go by, so you've got a value that you can put to something which describes something, it might not be the whole picture, it's certainly part of it though' (Physio 03)* *'actually, having a physio S&C team who are actually buying into the same process to go … he he believes it's really important, I believe it's really important and I think last year when we tried to implement it erm, we didn't have that, so in a sense it was like I think this is important then somebody else just going yeah I*

	don't think that's important, and it was like well … You hit a brick wall' (S&C Coach 04) *'they know I'm a caring person and I'm looking out for them as a person not them as a player, so I'm also saying what's best for them as a person and I think if you're right as a person, you're right as a player' (Physio 05)* *'I genuinely believe it has value, which we need to be doing and actually I think we should, probably should be better at doing it' (Physio 05)* *'from the practical side for my point of view, if we've got objective markers that then match or don't match with this, then that's when it becomes even more valuable, because if you've got players who've are red on here and their objective markers are, like red as well, then like you say you've got double ammo to go to the coaches and be like this guy's high high risk' (Physio 06)* *'I think well, I just think in terms of physical preparedness for your job, if you can show like you've got the evidence of this is what players do in this week why are they doing it OK like ultimately it's to build robustness, everyone uses this word robustness but what is robustness? Well it's chronic load but with a base of high level high base of fitness, you built chronic load on someone who's unfit they're probably going to break at some point' (S&C Coach 06)* *'hopefully like the fact that the ECB are now prioritising it more with their minimum standards and stuff, then hopefully that will then get the message that actually it's like they're doing that for a reason, cos its important and it gets more backing' (Physio 06)*
Player adherence	*'I thought that compliance, and general adherence would be quite poor erm there, and I individualise it so more of my younger players, I will give them the app to fill out and say this is really important do this, do that, and they will follow suit but the older more experienced players I actually just ask them' (S&C Coach 01)* *'Adherence is always I think a tricky one, so we setup a net-based system which players should fill out daily, but I would say probably averagely we get about 16 15 people filling it out a day, which is probably maybe 6 to 7 don't fill it out a day, that that those people can change each day' (Physio 02)* *'ultimately it's not up to, you know it is up to us to try and educate them more than anything, that's what I think we're trying to do is really educate as to why they should be filling out the app not telling them they have to do' (Physio 02)* *'like we try and educate them a bit in terms of like, this is why we're doing it, but if I'm honest, we try and avoid too many conversations with it, like we don't want them to think we're putting the handbrake on them' (S&C Coach 03)* *'they know that we do stuff with it so I think on the whole its its, its easy adherence on the whole, I think there's a few that can be tricky maybe, less than 10% really, probably like 2 guys who just sort of every day they're on that list' (S&C Coach 04)* *'It's such a mix, I mean you've got some really professional ones and some, they couldn't care less' (Physio 06)* *'we set it up, so they get lots of notification reminders' (S&C Coach 02)*

(Strategies to improve adherence)	*'we educate them definitely; we just want to know how they are … to help them to help the team; everything is geared towards us being the best cricket team we can be' (S&C Coach 02)* *'They ask why and rightly so, and if you can't explain it, you probably shouldn't have it in your programme' (S&C Coach 02)* *'I don't think it is a handbrake either I think it's there in order to try and promote people being able to play an-and be involved in the environment for as long and as much as we can possible as possible, so it's … but I think if you're not careful it can seen as a handbrake, but it's not there to be that, we want to try and promote cricket' (Physio 03)* *'we've done enough to try and explain to them that we're just trying to keep them on the park, erm I think because we've got a small squad I think they appreciate that we're not, it's not necessarily making selection decisions, so it's not being used against them, which I think's pretty helpful, I think if we had a bigger squad and it was actually used to rotate players around, which it could it could be used for, then I think there might be a little bit more resistance to it' (S&C Coach 04)* *'Players are good at doing it if they see why they're doing it' (Physio 05)*
Player monitoring challenges	*'that in football you know, your whole preparation is led up to 1 game in a in a 7-day block potentially 2 in 7, we're playing 5 of sometimes 5 or 6 of 7, and actually so that that 1 day off or that those 2 days off, you know there's no chance we're going to be going, right actually we need you in to do this this and this' (Physio 02)* *'it's when guys come back and they've been in and out the team, or there's been a change of format that we seem to get more issues, so it's about bridging that gap between workloads' (S&C Coach 02)* *'the biggest challenge I've had working with the players across the 4 years I've done it is … you're taking more data from me you know; how much do you need to know?' (Physio 05)* *'It's probably not used, it's not communicated to the players, I keep an eye on it and then it goes via the coach, so it can almost, it can help support like we're seeing this the numbers actually back it up, the coach can have a conversation with the player' (S&C Coach 06)* *'the frustrating thing like every injury we've had is … quite few associated with workloads but then you also get your ones that are not' (S&C Coach 06)*
(Resource)	*'It's a battle to be honest w-w- we're a 4-man team, and we really struggle to get to get ourselves together on a consistent basis' (Physio 01)* *'We're quite, we're quite limited with what we've got resource wise but I actually quite like that because it keeps it simple and consistent' (S&C Coach 02)* *'the budget we're given, and the facilities are the biggest factor and then maybe old schoolness of the culture' (Physio 06)*

	'unfortunately, a lot of it (analysis) is retrospectively looking back and going er maybe or maybe not, and the season rolls on so quickly you have to roll with it and it's difficult because you've got players that need rehabbing, or players that need that gym session or that intervention and er I'd love to be getting into, personally if it was me, I'd love to go back and look at that data retrospectively as much as possible' (Physio 01) *'I find it more reflective, so what we've done all the injuries we've had here erm, I then look at what was their acute to chronic at the time, so was it really relevant to the injury and then can you just piece together maybe why that injury had occurred erm, the annoying thing is about it its very much reflective after its happened' (S&C Coach 06)*
Use of GPS	*'It's more of a research thing rather than doing it consistently, it would just be to have an even greater understanding about what play certain players running loads look like between a 4 day 50 over and T20 games, erm and know what the potential return to running programmes could look like that are a bit more accurate' (S&C Coach 02)* *'We don't have GPS like we don't we don't have the ability t, to track high speed running or, you know we don't have the whether we invest in that or not I don't know I I'm more o-of the opinion that we should just max out these more, erm, simple methods of analysis before we then invest in GPS' (S&C Coach 04)*
(Positive perception of GPS)	*'we know roughly there's a lot of GPS we know roughly what a bowler covers in a day, roughly how much high-speed running they cover for each format, it's all individual, but we know we've got an idea of that and to be fair that data helps us pre-season' (S&C Coach 03)* *'GPS backs up evidence of that and it can give, I think from like a rehab point of view with (physios) as well, like collecting their top speeds collecting their erm .. data from rehab so when they come back, we kind of we've got a more objective measure as to are they ready to perform' (S&C Coach 03)* *'now I know some of the GPS data we've seen erm suggests that actually some guys bowl harder in training than they do in a match, erm so we had one pers- so our stress fracture actually at the moment his, his peak, erm overload was training overs not match overs' (Physio 05)* *'in terms of prepping the guys, what I would prep them for? What do their bodies go through in a day of champo cricket, high speed metres, top end metres, maximum sprinting? … at the end of the day when they walk off the field, what's their body had to cope with? Erm and then from that, that kind of drove then my prep in the winter' (S&C Coach 06)*
(Negative perception of GPS)	*'they're also on our seamers and we look at different variables on that from distance covered to different running thresholds velocities erm, we're yet to do accelerations, but is something I would like to do in the future erm, and looking at max velocity and we just track erm, if they've hit max velocity for the week etc, things like that really, erm that's quite tedious I find … It's getting to the point now where, erm a lot of the information is same same coming back' (S&C Coach 01)* *'he's actually asking me whether he can have a couple of games break from wearing the GPS, he wants to get his rhythm back' (S&C Coach 01)*

	'I would love to be able to GPS the guys, without having to have them wear GPS's' (S&C Coach 02) *'Some of the bowlers flatly do not like wearing them' (S&C Coach 02)* *'yeah, it's a cost thing and a lot of our players have experienced them and worn them and some are happy and others are like, 'no I'm not wearing them', erm 'cos it interferes with their bowling' (S&C Coach 02)* *'it's the effectiveness of the information that you get from it as well, is it is all the hours that you're going to put into it, more valuable than what you would be able to spend those hours on? Rather than being able to then put all your hours into that then analyse that data and is that going to inform practice and be as effective as what you would be able to do, if you weren't to spend all of that time that you put in now?' (Physio 03)* *'I'd like to have some more GPS data probably like we did do … Like last year I collected a bit but I was doing it myself, it was a pain in the arse like' (S&C Coach 03)* *'so, they're fine for like speed distances, and then unless you individually try and crop each ball and make them into an over, which would take you forever you can't really do it, so like the system wasn't very fast either, so it was partly like man hours' (S&C Coach 03)* *'it's a tight-fitting vest so a few of them don't like it, erm but I think the big issue we have is that its designed for rugby and football wearing something say for 80 90 minutes, these guys are wearing it for 6 hours and starting to get rashes and stuff' (Physio 05)* *'had a few arguments with some when they weren't playing so well and threw it back at you' (S&C Coach 06)*
Pre-season preparations	*'I think the number of overs bowled in pre-season is a massive factor' (Physio 01)* *'It's building them up and keeping them there' (S&C Coach 02)* *'Yeah, for me it has to be, it has to be scaled like you're not, you're trying to look at your starting point of when your competitive season is and almost work back and almost just chip away a little bit workload wise so it's almost like that, start with a small house and build up until you've got your skyscrapers' (S&C Coach 02)* *'I think there's a difference in competitive overs to net overs and warm up overs. I think the intensity of championship cricket is so much higher than 2nd eleven and their overs, you can prep all you want in terms of the amount of the overs you bowl in a net scenario, but when you get in that 1st game, you're going up another 10%, and its subconscious so actually getting them into that competitive mode, I think it's just another step up' (Physio 02)* *'us definitely going away with pre-season has been good for us, has been helpful' (Physio 02)* *'you know that in those Champo cricket as well when you start in the start of the season, so the work bowling volumes are really high, and if the intensity hasn't*

	been prepared for and the volume hasn't been prepared for then you know obviously, you're going to get problems' (S&C Coach 04) *'bowling and cricket takes priority ahead of anything S&C wise because ultimately that's what they've got to do, that helps support the cricket but the cricket is still priority number one' (S&C Coach 02)*
(Challenges with pre-season preparations)	*'say after January you start building up bowler's workloads up, you start building their overs up in the nets and then you start to add in the batter erm, so unless you've got a marquee where you can get a full run up as it's tough to get erm, get that intensity of the overs in, but yeah so we that's the way it would generally go, you might bowl indoor then you might add in batters to make it more competitive, but it's not off a full run up, its off a different service' (S&C Coach 03)* *'biggest challenge is that go to pre-season tour and the volume and intensity goes up because their bowling outdoors, full run up in the heat and their bowling in matches, so both are going up, which we know is a risk anyway so that's the challenge' (S&C Coach 03)* *'we try to gradually build overs into, through pre-season bowling our biggest issue is like, where to bowl … so we have a little bit inside but we don't have a full run up, er players don't like bowling indoors, coaches don't like players bowling indoors … so you basically and then if you go outside its weather, so the issue being is that you're trying to build overs in March, but you can't guarantee you've got 20 good days in March ' (Physio 05)* *'it's more the floor for me, our floor in there is concrete rock-hard surface, tendons things like that, that change of surface going indoors to outdoors it's not just … possible, damage that they could do indoors, but its then that transfer out on grass' (S&C Coach 06)* *'Yeah, so like much more going down that route of less, I want guys bowling and I think like … again you come up with different theories every year and like this year I'm thinking well … why don't we do more volume of low intensity overs?' (S&C Coach 06)* *'let's go onto the 4G now running off half a run up, the overs are going to come down and then when we're first out on grass, OK now you're off your full run overs might come down again, but then they go up to match' (S&C Coach 06)* *'so, I mean preseason tour because like, we've been very lucky the last 2 years as we've actually gone previous years, we've had like a a marquee as well, which again you put basically a marquee over the nets at the back train outside' (S&C Coach 06)*
Management/coach support and culture	*'we just make suggestions, so we report to the coaches erm, but ultimately it's their decision' (S&C Coach 02)* *'we can definitely put stuff or processes in place, which will try and stop injuries from happening and when they do happen we try and get our players back fitter stronger and robust to to get back playing and contributing to winning games, but ultimately the team culture will probably override that, erm luck will override that, you know we've seen some of the injuries this year these dislocated shoulders, you know you can't tell me a physio a medical team in the world that's going to tell you who's at risk of dislocating a shoulder (laughs)' (Physio 02)*

	'all I think you can do as science and medicine, you can lay out the risks and the rewards, or the the pros and cons the benefits, however you want to put it erm and the coaching staff have to then take that information and ultimately, they're the ones that are accountable for the win and losses' (Physio 02)
(Negative management/coach support and culture)	*'but then again you are very limited in erm … not your ambitions as practitioners working in this environment but … you're limited by the buy-in from the coaching staff' (Physio 01)* *'it doesn't seem that trends in injury are changing that much and we are still having the same incidence of and the same types of injuries year on year so ... so, y-you can sometimes sympathise or understand er a skills coach's frustration, erm when talking around monitoring workloads because, if there's they're not seeing change then why would you, why would you buy-in?' (S&C Coach 01)* *'probably players attitudes to science and medicine, coaches' attitude to science and medicine, I think cricket's attitude to science and medicine… I think cricket's attitude's changing but and I think at England level it's already bought into massively and you know, and I think at some I think we've spoke about already, a little bit at bigger clubs are buying into it now' (Physio 05)* *'I think the professionalism in the sport; the pay in the sport has gone up really quickly and really high and I think the culture's still quite behind' (Physio 06)* *'the budget we're given, and the facilities are the biggest factor and then maybe old schoolness of the culture' (Physio 06)*
(Positive)	*'so, the purpose for me is just to inform. Erm, I think coaches haven't got to where they've got without having good a good understanding of players, they know what makes them tick, they know how they're responding you know, they don't need us to tell them that, but I think it's very nice for a coach when they've got the objective data to back up what they're thinking' (Physio 02)* *'the nice thing this club has done is they've, they've tried to explain to each player individually and as a group that everything is done to try and help us win' (Physio 02)* *'our previous S&C he he, was fantastic at building a culture that of just boys that loved S&C … embed it early, get that culture so that when they get to academy, they know what it's about, they know that its part and parcel of being a professional cricketer' (Physio 02)* *'if you walk into an environment where you feel like, you know the club believe it, they invest in proper facility here for me as a player' (S&C Coach 06)*

APPENDIX F: Physical Profiling Measure Descriptions (Chapter 7)

Physical Profiling Measure	Description
Height	Subjects measured in centimetres (cm) with shoes removed, using the stretch stature method. Stature is the maximum distance from the floor to the vertex (highest point on the skull when head is held in Frankfort plane) of the head.
Weight	Subjects weighed in kilograms (kg) with any excess clothing removed. Weight recorded to nearest 0.1 kg.
Body Mass	Assessments conduced in accordance with the International Society for the Advancement of Kinanthropometry (ISAK) protocols.
Sum of 8 skinfolds	A skinfold calliper is used to assess skinfold thickness in millimetres. Measurements taken for biceps, triceps, sub-scapular, iliac crest, supra-spinal, abdominal, front thigh and medial calf.
Total shoulder range of motion	Subject in crook lying with no pillow under their head. Shoulder is abducted to 90 degrees with deltoid insertion at edge of the plinth. Elbow flexed to 90 degrees and forearm in mid prone. The tester passively rotates the shoulder into internal and external rotation until a firm end point is reached or the scapula or head of humerus begins to move. Angle of internal and external rotation is recorded. If the subject reports any pain the test is stopped at the onset of pain.
Combined elevation	Subject is in prone with their forehead on the floor, arms outstretched overhead with the hands clasped together and the elbow straight and thumbs pointing skywards. The subject is instructed to lift their arms as high as possible off the floor in a smooth movement whilst keeping elbows straight and forehead on the floor. The tester records the point the ulna styloid reaches to the nearest 0.5cm. Test is repeated two times and the best score recorded.
Dorsiflexion lunge test	Subjects are instructed to lunge forward until their knee touches the wall. The heel is required to remain in contact with the floor at all times. The foot is moved away from the wall to the point where the knee can only make slight contact with the wall, while the heel remains in contact with the floor. This puts the ankle joint in maximal dorsiflexion. The leg not being tested can rest on the floor and participants are allowed to hold the wall for support. The maximum distance from the wall to the tip of the big toe is recorded in centimetres (cm).
Single leg rotation	Subject stands with their feet pointed straight ahead and hip width apart. Balancing on the leg not being tested, the subject lifts the leg being tested until their knee is at waist level. Rotating the hip the subject brings the lifted leg toward the side of their body, holds and then back to the front.
Total hip range of motion	Internal and external rotation assessed. For internal rotation the tester passively rotates the hip into internal rotation. The subject is instructed to allow their hips to fall into their position keeping their knees together. When the subject reaches end of range the tester records the angle of hip internal rotation by placing an inclinometer on the medial aspect of the tibia just distal to the medial tibial plateau. For external rotation, the tester passively moves the hip into external rotation. The tester stops the motion when a firm end feel is reached or the pelvis begins to rotate. The range in degrees is recorded. If the subject reports pain the range of hip flexion at onset of pain is recorded.

Grip strength	Quantified by measuring the amount of static force that the hand can squeeze around a dynamometer.
Total thoracic spine rotation	Sitting over the edge of a box. Hold a stick with arms crossed. Rotate to right and then left. Measure degrees of movement in both directions.
Rotator cuff external and internal rotation	Subject is in 90 degrees of glenohumeral joint abduction, 90 degrees of elbow flexion, and neutral supination/pronation forearm position. The subject is asked to keep their elbow at 90 degrees and move the forearm upwards as high as they can and then downwards as low as they can. The external rotation and internal rotation angles in 90 degrees of abduction are formed by aligning the goniometer with the ulnar styloid process, the olecranon process of the ulna, and a horizontal line in the horizontal plane.
Single leg hop & hold	Subject stands on one leg behind a marked line. Subject then hops forwards as far as possible whilst 'sticking' the landing and holding the landing position for 3 seconds. Subject performs up to 3 hops on each leg, but is also allowed sub-maximal warm up jumps. Distance is marked and measured from the line to the front of the landing foot. Quality of movement is assessed from both front-on and side-on.
Broad jump	Subject stands on two legs with heels on a marked line. The subject then jumps forwards as far as possible whilst 'sticking' the landing and holding the landing position for 3 seconds. Subject performs up to 3 hops, but is also allowed sub-maximal warm up jumps. Distance is marked and measured from the line to the heel of the foot (shortest distance). The quality of the movement and distance is assessed from both front-on and side-on.
Sumo Deadlift - 5 rep maximum	Subject stands with feet wider than shoulder-width apart, and their toes point out at a 45 degree angle. The subject then bends at the hips to lower and grab the bar with either an overhand or mixed grip. Ensuring back is flat in this bottom position the subject then drives through their heels and extends their knees and hips to lift the bar to mid-thigh height. The subject pulls their shoulders back at the top of the move then carefully lowers the bar back to the ground. The weight that can be lifted for a maximum of 5 repetitions is recorded in kilograms.
Hip thrust - 5 rep maximum	Subject sits with their shoulders and shoulder blades against a bench. A barbell is rolled over the legs until it's directly over their hips. The subject puts their elbows on the bench and hands on the bar to steady it. Ensure the subject's body is aligned and spine is neutral. The subject then braces their core, drives through their heels and squeeze their glutes to lift their hips (and barbell). The subject comes down smoothly with core still braced. The maximum weight that can be lifted for 5 repetitions is recorded in kgs.
Triple hop test	The subject jumps as far as possible on a single leg three consecutive times, without losing balance and landing firmly. The distance is measured from the start line to the heel of the landing leg.
10m, 20m, 30, 40m speed	Subjects complete a standardised warm up. Measure a 20m or 40m lane placing timing gates at 0m, 10m, 20m, 30m and/or 40m. The first gate is set at a height of 0.5m, the rest are set at a height of 1m. Mark the start line at 0.5m before first timing gate with tape. Subjects begin each trial from stationary start with the toe of their front foot on the start line. Subject must be visibly static with no countermovement or sway. Subjects are allowed 3 trials with a minimum of 3 minutes between trials. Time recorded to nearest 0.01 second.

Run Two	Subjects complete a standardised warm up. The test is set up at a standard wicket with a timing gate at one end. If a wicket is not available, a distance of 17.68m is marked out. An additional timing gate 5m from the turn will allow greater analysis of this test as this will specifically measure speed in and out of the turn. A static camera is set back 6-8m to capture this footage. This can act as a cricket specific 5-0-5 test within the main test. A start line is marked with tape 0.5m before the first timing gate. Subjects begin each trail from stationary start with the toe of their front foot onto the start line and the bat held in front of them with 2 hands. Subjects must be visibly static, with no countermovement or sway. Subjects spring to the far batting crease, ground their bat behind the crease, turn and sprint back through the timing gates. Subjects must ground their bat through the finish line. Subjects must avoid breaking the beam of the gates with their bat. Subjects are allowed 2 trials either side of their turn with a minimum of 3 minutes between trials. Times are recorded to the nearest 0.01 second.
505 agility test	Subject accelerates maximally to a 15m line, turn on their right leg and sprint back 5m through the finish line as quickly as possible. During the turn, the participant must not touch their hand down on the floor. The subject repeats this again, but this time performs a left leg turn and continues to alternate. The subject must touch the 'turn-around line' on each effort, failing to place their foot on, or across the line, results in a failed attempt. Each subject completes a minimum of three efforts, each separated by a 2-3 minute rest. The sprint is timed with a stopwatch in seconds. The average of the three efforts is recorded. Times are recorded to the nearest 0.01 second.
Yo-Yo	Cones are used to mark out 3 lines, with 2 lines 5m apart and 1 20m from the other. Subjects starts behind the middle line and begins running when signalled by the beep. They turn at the top cone and run back to the starting point when signalled by the beep. There is an active recovery period of 10 seconds between every 40m shuttle, during which the subject must walk or jog around the bottom cone and return to the starting point. A warning is given when the subject does not complete a successful shuttle in the allocated time and the subject is removed from the test after 2 consecutive warnings. A warning is also given if the subject fails to intersect the 20m line with their foot when turning i.e. do not allow subjects to turn short of the line. False starts are prohibited as they give subjects extra time to complete the shuttle. False starts should be punished with a warning. The last completed shuttle is used as the performance score.

APPENDIX G: Generalised linear mixed effect models outputs (Chapter 7)

Model 1

2,399 observations

Table 1: Model 1 output

Predictors	Risk ratios	95% CI	p- value
(intercept)	0.02	0.02-0.03	<0.001
Differential 7-day (linear)	0.98	0.83-1.16	0.79
Differential 7-day (polynomial)	1.24	1.13-1.36	<0.001
Broad jump average	0.7	0.51-0.96	0.03
30 m speed	0.31	0.18-0.54	<0.001
40 m speed	2.17	1.21-3.86	0.009
Dorsiflexion lunge test (right-side)	0.77	0.60-0.97	0.03
Single leg hop (left)	1.79	1.48-2.17	<0.001

Table 2: Model 1 performance

AIC	BIC	Conditional R2	Marginal R2	ICCC	RMSE	Log loss	Log score	Spherical score
702.09	754.13	0.40	0.39	0.02	0.18	0.14	-3.60	0.01

Model 2

2,795 observations

Table 3: Model 2 output

Predictors	Risk ratios	95% CI	p- value
(intercept)	0.02	0.01-0.04	<0.001
Differential 7-day (linear)	0.98	0.83-1.15	0.79
Differential 7-day (polynomial)	1.2	1.10-1.32	<0.001
Broad jump average	0.46	0.33-0.65	<0.001
30 m speed	0.36	0.20-0.65	0.001
40 m speed	0.69	0.33-1.16	0.33
Dorsiflexion lunge test (right-side)	0.64	0.39-1.06	0.08

Table 4: Model 2 performance

AIC	BIC	Conditional R2	Marginal R2	ICCC	RMSE	Log loss	Log score	Spherical score
778.42	825.91	0.67	0.36	0.48	0.18	0.13	-3.49	0.01

Model 3

3,120 observations

Table 5: Model 3 output

Predictors	Risk ratios	95% CI	p- value
(intercept)	0.02	0.01-0.04	<0.001
Differential 7-day (linear)	0.99	0.84-1.16	0.88
Differential 7-day (polynomial)	1.19	1.09-1.30	<0.001
Broad jump average	0.51	0.38-0.68	<0.001
30 m speed	0.31	0.20-0.50	<0.001

Table 6: Model 3 performance

AIC	BIC	Conditional R2	Marginal R2	ICCC	RMSE	Log loss	Log score	Spherical score
813.92	868.20	0.67	0.39	0.45	0.17	0.13	-3.44	0.01

Model 4

3,120 observations

Table 7: Model 4 output

Predictors	Risk ratios	95% CI	p- value
(intercept)	0.02	0.01-0.04	<0.001
Differential 7-day (polynomial)	1.19	1.09-1.30	<0.001
Broad jump average	0.51	0.38-0.68	<0.001
30 m speed	0.32	0.20-0.50	<0.001

Table 8: Model 4 performance

AIC	BIC	Conditional R2	Marginal R2	ICCC	RMSE	Log loss	Log score	Spherical score
829.95	860.17	0.66	0.39	0.45	0.17	0.13	-3.44	0.01

Model 5

2,399 observations

Table 9: Model 5 output

Predictors	Risk ratios	95% CI	p- value
(intercept)	0.02	0.01-0.04	<0.001
Differential 7-day (polynomial)	1.23	1.12-1.35	<0.001
Broad jump average	0.54	0.40-0.74	<0.001
30 m speed	0.39	0.25-0.60	<0.001
Single leg hop (left)	1.84	1.34-2.52	<0.001

Table 10: Model 5 performance

AIC	BIC	Conditional R2	Marginal R2	ICCC	RMSE	Log loss	Log score	Spherical score
703.31	738.01	0.50	0.34	0.24	0.18	0.14	-3.60	0.01

Model performance comparison

Table 11: Model performance comparison organised by conditional R2 descending

Model	Type	AIC	BIC	Conditional R2	Marginal R2	ICCC	RMSE	Log loss	Log score	Spherical score	Performance score
mod2	glmerMod	778.42	825.91	0.67	0.36	0.48	0.18	0.13	-3.49	0.01	0.55
mod3	glmerMod	831.92	868.20	0.67	0.39	0.45	0.17	0.13	-3.44	0.01	0.55
mod4	glmerMod	829.95	860.17	0.66	0.39	0.45	0.17	0.13	-3.44	0.01	0.55
mod5	glmerMod	703.31	738.01	0.50	0.34	0.24	0.18	0.14	-3.60	0.01	0.52
mod1	glmerMod	702.09	754.13	0.40	0.39	0.02	0.18	0.14	-3.60	0.01	0.53